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MEASUREMENT OF THE CROSS SECTION FOR ELASTIC
SCATTERING OF ELECTRON NEUTRINOS ON ELECTRONS

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
Neville D. Wadia
B.Sc.(Hons.). Indian Institute of Technology, 1991
M.S.. Louisiana State University. 1995
December. 1998
To my parents,
Zarine and Dinyar Wadia
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ABSTRACT

In this dissertation, we measure the cross section for the elastic scattering of electron neutrinos on electrons. We use data from the LSND experiment which is located at the Los Alamos Neutron Scattering Center at Los Alamos National Laboratory, New Mexico. The neutrino beam is produced when an 800 MeV proton beam from a linear accelerator is incident on a target located 29.8 m from the detector. The LSND veto system allows us to reject charged cosmic-ray particles entering the detector with high efficiency. The detector consists of 180 tons of mineral oil, to which a small quantity of scintillator is added. This combination enables us to detect both Čerenkov and scintillation light produced by highly relativistic charged particles. For the neutrino-electron elastic scattering process, we detect the recoil electron and require it to be scattered along the direction of the incident neutrino. This requirement has a large acceptance for the elastic scattering events while at the same time it reduces the background due to other processes. We obtain $133 \pm 22$ events for the $\nu_e e^- \rightarrow \nu_e e^-$ process and measure a cross section, $\sigma = [11.6 \pm 1.9(stat.) \pm 1.4(syst.)] \times E_{\nu_e}(\text{MeV}) \times 10^{-45}\text{cm}^2$, for this reaction. The average energy of the $\nu_e$ beam at LSND is 31.7 MeV. A feature of this reaction is that it can proceed through either charged current or neutral current interactions. The standard model of electroweak interactions predicts a destructive interference between these two channels which leads to a reduction in the cross section from its value had there been no interference. We measure the strength of this destructive interference.
$I = -0.88 \pm 0.22(stat.) \pm 0.11(syst.)$, and compare it to a value of $I = -1.08$ predicted by the standard model of electroweak interactions.
CHAPTER 1

INTRODUCTION

In this dissertation, we present a measurement of the cross section for the elastic scattering process.

\[ \nu_e + e^- \rightarrow \nu_e + e^- . \]

This purely leptonic process is of interest because it proceeds via both charged current and neutral current interactions. There exists an interference term between these two channels. The standard model (SM) of electroweak interactions predicts a destructive interference effect whose strength we will measure and compare with its SM value.

The data was obtained at experiment E1173, also known as the Liquid Scintillator Neutrino Detector (LSND) experiment. The LSND collaboration is listed in the Appendix. This experiment is located at the Los Alamos National Laboratory, New Mexico. The neutrino beam is produced by an 800 MeV proton beam which is incident on a target 29.8 m from the detector. The detection apparatus consists of a 180 ton tank, filled with liquid scintillator and surrounded by a veto system.

1.1 Overview

Let us briefly sketch the organization of this dissertation. We will describe the theory for the \( \nu_e e^- \rightarrow \nu_e e^- \) elastic scattering process in Chapter 1. The
production of the neutrino beam is discussed in Chapter 2. The LSND detector and the data acquisition system are described in Chapters 3 and 4 respectively.

We will describe the event reconstruction procedure in Chapter 5 where the raw data from photomultiplier channels is processed into event information that can be used for our analysis. Chapters 6 and 7 are devoted to the event selection procedure and in Chapter 8 we present the results of our analysis. Finally, the conclusions are presented in Chapter 9.

1.2 The Electroweak Force

A common aim of all science is to explain as many facts as possible with a few simple principles. There have been and continue to be efforts to correlate apparently different phenomena and, if possible, achieve a unification, wherein the source of these phenomena are explained by one common set of hypotheses.

The study of fundamental forces is an example of this process of unification. Our present-day understanding dictates that matter is composed of quarks and leptons. They are termed as "elementary particles" and there exist three generations for both quarks and leptons.

\[
\begin{align*}
\text{quarks} & : \begin{pmatrix} u \\ d \\ c \\ s \\ t \\ b \end{pmatrix} \\
\text{leptons} & : \begin{pmatrix} \nu_e \\ e \\ \nu_\mu \\ \mu \\ \nu_\tau \\ \tau \end{pmatrix}
\end{align*}
\]

There are four fundamental forces in nature which cause interactions between the elementary particles. They are listed below in the order of increasing magnitude.
1. Gravitational.

2. Weak.

3. Electromagnetic. and

4. Strong.

The electromagnetic and the weak forces were unified by the Weinberg-Salam theory [1, 2, 3] of electroweak interactions. We will briefly discuss this unification process, mentioning some historical developments in what is currently called the standard model of electroweak interactions.

In 1865, Maxwell unified two seemingly different branches of physics, electricity and magnetism, when he proposed a single theory of electromagnetism [4]. Later, efforts were made to include quantum physics and relativity into electromagnetism, yielding the field theory of quantum electrodynamics (QED). By the 1940s, a complete and renormalizable QED theory was constructed [5, 6, 7]. It has been phenomenally successful in making detailed predictions of electromagnetic effects and became a model for all future theories of particle interactions.

In the meantime, the observation of nuclear beta-decay signalled the presence of another force, the weak nuclear force. A beta-decay occurs when a proton, within the nucleus, changes into a neutron with the emission of a positron. Since there were no traces of other particles, it was naturally assumed that the positron was the only particle emitted in beta-decay. This assumption led to the following anomalies. The positron, in most cases, did
not carry away the full amount of energy available from the nuclear transition. Thus instead of a monoenergetic spectrum, one observed a continuous positron energy spectrum. Also the law of conservation of angular momentum seemed to be violated for beta-decay. To remedy these anomalies, Pauli, in 1930, postulated the presence of a neutral spin one-half particle, which is emitted in beta-decay along with the positron [8]. This particle, named "neutrino" (little neutral one) by Fermi, would participate only through weak interactions. It would account for the invisible energy and conserve angular momentum in beta-decays.

Fermi then suggested a theory of beta-decay [9] by introducing a 4-fermion interaction. This theory was inspired by the structure of electromagnetic interactions in QED. A 4-fermion interaction for neutron decay is shown in Fig. 1.1. The invariant amplitude, $\mathcal{M}$, for this decay is given as

$$\mathcal{M} = G_F (\bar{n} \gamma^\mu p)(\bar{\nu_e} \gamma_\mu e),$$

where $G_F$ is a weak coupling constant termed the Fermi constant.

The occurrence of Gamow-Teller [10] transitions in addition to Fermi transitions in beta-decays indicated that the Lorentz structure of the 4-fermion interaction could not be purely vector ($V$) as hypothesized by Fermi. We now know that the charged current-current interaction is ($V$-$A$) and parity is violated for this interaction.

However, until the late 1950s parity was thought to be conserved for all forces, including weak interactions. In 1956, Lee and Yang made a critical survey of all weak interaction data and suggested that parity was not conserved for weak interactions [11]. Soon a variety of experiments [12, 13, 14, 15]...

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confirmed the parity violation effect in weak interactions. A (V-A) theory [16, 17, 18], in fact, suggested maximal parity non-conservation. Indeed by 1959, the weak interactions were confirmed to have the (V-A) structure with Fermi’s original $\gamma^\mu$ replaced by $\gamma^\mu(1 - \gamma^5)$.

Continuing with the story of unification, the long ranged electromagnetic force seemed very different from the short ranged weak nuclear force. The electromagnetic force is mediated by the photon, which being massless, explains the long ranged nature of the force. A natural way to explain the short ranged nature of weak interactions (just $10^{-16}$ m) is to assume that the carrier of the force is very heavy. Thus the W boson was postulated and later estimated to be approximately 100 times the mass of a proton.

The weak interactions are now known to proceed through two channels, the charged current (CC) and the neutral current (NC). The charged current reaction involves the exchange of a charged W boson. Here, if a neutrino
enters the reaction, its partner, the charged lepton, will be produced due to the $W$ exchange. The neutral current reaction involves no exchange of charge. Thus a reaction initiated by a neutrino proceeds via the exchange of a neutral $Z$ boson and produces a neutrino in the final state.

Until now, whenever we mentioned weak interactions we were implicitly referring to charged current weak interactions. This is because the early experiments only detected events of the charged current variety. There were no indications of weak neutral current interactions. In particular, during the 1960s, there were extensive efforts to find flavor changing weak neutral currents in the decay of strange particles [19, 20, 21, 22]. The absence of the flavor changing weak neutral currents was erroneously interpreted as the absence of all neutral currents.

However, a renormalizable theory of electroweak interactions had been proposed which required the presence of both charged current and neutral current interactions. In addition to the charged $W$ boson, the Weinberg-Salam theory [1, 2, 3] predicted the existence of a neutral $Z$ boson, the exchange of which lead to neutral currents. Hence the absence of neutral current interactions was a major problem towards the unification of weak and electromagnetic forces.

It was not until the early 1970s, when energetic neutrino beams became available, that the first neutral current weak interaction events were detected both at CERN [23, 24] and Fermilab [25]. Also in 1970, the GIM mechanism [26] explained the absence of flavor changing weak neutral currents and served to establish the Weinberg-Salam theory. Additional confirmation was
presented in 1983 when CERN announced, in quick succession, the discoveries of the W boson \[27, 28\] and then the Z boson \[29, 30\]. All this firmly established what we currently call the standard model of electroweak interactions.

Within the standard model, the neutrino is, by definition, a massless particle. As a result, its helicity is fixed: the neutrino is left-handed and its anti-particle right-handed.

1.3 Electron Neutrino-Electron Elastic Scattering

The neutrino interacts through weak interactions only. Neutrino-electron elastic scattering is a clean reaction, involving two point-like objects. There are no hadronic components to this reaction. In this dissertation, our goal is to measure the electron neutrino-electron elastic scattering cross-section. This reaction can occur via both the charged current and the neutral current channels, as shown in Fig. 1.2.

1.3.1 The Charged Current Reaction

The CC reaction, as discussed previously, has a (V-A) structure. The Lagrangian can be written as \[31\]

\[
\mathcal{L}^{CC} = -\sqrt{2}G_F (\bar{\nu}_e \gamma_\mu \frac{1 - \gamma^5}{2} e)(\bar{e} \gamma^\mu \frac{1 - \gamma^5}{2} \nu_e).
\]

For later convenience, we perform a Fierz reordering, whereby we exchange two lepton terms within the Lagrangian \[31\]. This results in an overall negative sign.

\[
\mathcal{L}^{CC} = \sqrt{2}G_F (\bar{\nu}_e \gamma_\mu \frac{1 - \gamma^5}{2} e)(\bar{e} \gamma^\mu \frac{1 - \gamma^5}{2} \nu_e).
\]
The massless neutrino is a left-handed particle in the standard model. However the electron can have a right-handed as well as a left-handed component. The \((1 - \gamma^5)\) term couples to the left-handed component of the electron while a \((1 + \gamma^5)\) term couples to the right-handed component.

From the expression for \(\mathcal{L}^{CC}\) we see that CC interactions couple only to the left-handed component of the electron. Writing the Lagrangian to explicitly emphasize the handedness we have,

\[
\mathcal{L}^{CC} = \frac{G_F}{\sqrt{2}} (\bar{\nu}_e \gamma_\mu \frac{1 - \gamma^5}{2} \nu_e) (\bar{\nu}_e \gamma_\mu [g_{l}^{cc} \frac{1 - \gamma^5}{2} + g_{r}^{cc} \frac{1 + \gamma^5}{2}] e),
\]

where \(g_{l}^{cc} = 2\) and \(g_{r}^{cc} = 0\).
1.3.2 The Neutral Current Reaction

The form for the NC reaction is not (V-A) and involves replacement of the $\frac{1}{2}(1 - \gamma^5)$ term by [31]

$$\frac{1}{2}(c_v - c_a \gamma^5).$$

where $c_v$ and $c_a$ are the vector and axial-vector components. In the standard model (SM) these coefficients, for electrons, are given by [31]

$$c_v = 2\sin^2 \theta_W - 1/2$$

and

$$c_a = -1/2.$$ 

whereas, for neutrinos, they are

$$c'_v = 1$$

and

$$c'_a = 1.$$ 

The angle $\theta_W$ is the Weinberg angle or the weak mixing angle of the SM. For the NC reaction, the Lagrangian term is then

$$\mathcal{L}^{NC} = \frac{G_F}{\sqrt{2}}(\bar{\nu}_e \gamma_\mu \frac{1 - \gamma^5}{2} \nu_\mu)(\bar{\nu}_\mu \gamma^\nu [c_v - c_a \gamma^5] e).$$

Again, writing it to emphasize the handedness, we obtain

$$\mathcal{L}^{NC} = \frac{G_F}{\sqrt{2}}(\bar{\nu}_e \gamma_\mu \frac{1 - \gamma^5}{2} \nu_\mu)(\bar{\nu}_\mu \gamma^\nu [g_l^{nc} \frac{1 - \gamma^5}{2} + g_r^{nc} \frac{1 + \gamma^5}{2}] e),$$

where

$$g_l^{nc} = (c_v + c_a)$$

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and

\[ g_r^{nc} = (c_v - c_a). \]

\( g_l^{nc} \) and \( g_r^{nc} \) are known as the electron chiral coupling constants.

The total Lagrangian for the electron neutrino-electron elastic scattering process is then

\[
L^{tot} = \frac{G_F}{\sqrt{2}} (\bar{\nu_e} \gamma_\mu \frac{1 - \gamma_5}{2} \nu_e) (\bar{e} \gamma^\mu [(g_l^{cc} + g_l^{nc}) \frac{1 - \gamma_5}{2} + (g_r^{cc} + g_r^{nc}) \frac{1 + \gamma_5}{2}] e).
\]

1.3.3 Kinematics

In the center of mass (CM) frame, the \( \nu_e e^- \rightarrow \nu_e e^- \) process involves a 2-body collision between two extremely relativistic point-like objects, as shown in Fig. 1.3. The primes distinguish the final outgoing particles from the initial incident particles.

![Figure 1.3: Neutrino-electron elastic scattering in the CM frame](image)

Let us define the Lorentz invariant quantity

\[
y = \frac{p_{e'}^\mu p_{\nu_e}^\mu}{p_{\nu_e}^\mu p_{e'}^\mu}
\]
where $p^*$ is the 4-momentum and final states are identified by primes. In the Lab frame

$$ y = \frac{E_{e'}}{E_{\nu_e}}. $$

where $E_{\nu_e}$ is the incident neutrino energy and $E_{e'}$ is the recoil energy of the electron which was initially at rest. Thus $y$ is the fractional energy imparted to the electron and

$$ 0 \leq y \leq 1. $$

The variable, $y$, along with the incident neutrino energy, $E_{\nu_e}$, completely describe the kinematics of the collision. In the Center of Mass (CM) frame, if $\theta$ is the angle of the outgoing neutrino with respect to the incident neutrino direction we have.

$$ y = \frac{1}{2}(1 - \cos \theta). $$

The total Lagrangian, $\mathcal{L}^{tot}$, is a sum of the left and right-handed components. The two components contribute incoherently towards the total cross-section. The differential cross-section is given by

$$ \frac{d\sigma}{dy} = \left[ (g_t^{cc} + g_t^{nc})^2 + (1 - y)^2 (g_r^{cc} + g_r^{nc})^2 \right] \sigma_0, $$

where

$$ \sigma_0 = \frac{G_F^2}{4\pi} E_{\nu_e}. $$

The $(1 - y)^2$ term, obtained when a left-handed neutrino is coupled to a right-handed electron, can be understood in terms of conservation of angular momentum. The back-scattering of the neutrino is disallowed, as shown in Fig. 1.4. Hence

$$ \cos \theta \neq -1, $$
which implies \( y \neq 1 \). The \((1 - y)^2\) term ensures that the cross-section vanishes at \( y = 1 \).

\[ \text{Forward: Allowed} \]
\[
\begin{array}{c}
\langle \quad \rangle \\
v_e & \quad e_R
\end{array}
\]
\[ J_z^{\text{initial}} = -1 \]
\[ J_z^{\text{final}} = 1 \]

\[ \text{Backward: Disallowed} \]
\[
\begin{array}{c}
\langle \quad \rangle \\
v_e & \quad e_R
\end{array}
\]
\[ J_z^{\text{final}} = 1 \]

Figure 1.4: Angular momentum conservation for the \( \nu_e e^-_R \rightarrow \nu_e e^-_R \) process.

In the case of \( \nu_e e^-_L \rightarrow \nu_e e^-_L \)

\[ J_z^{\text{initial}} = 0 \]

and there is no restriction on back-scattering. In fact the contribution to the cross-section from this term is isotropic in space. Also it is the dominant contribution to the cross-section as \((g^{cc}_l + g^{nc}_l)^2 \gg (g^{cc}_r + g^{nc}_r)^2\).

All experimentally measured quantities are defined with respect to the Lab frame of reference and, henceforth, the choice of the Lab frame will be implicitly assumed.
A characteristic feature of the $\nu_e e^- \rightarrow \nu_e e^-$ process is that, for most cases, the recoil electron is scattered along the direction of the incident neutrino. Let us define $\Theta$ as the angle between the direction of the recoil electron and the incident neutrino direction. Expressing $\cos \Theta$ in terms of the neutrino energy, $E_{\nu_e}$, and the energy of the recoil electron, $E_{e'}$, we have

$$\cos \Theta = \left[ 1 + 2 \frac{m_e}{E_{e'}} \left( 1 - \frac{E_{e'}}{E_{\nu_e}} \right) \left( 1 + \frac{m_e}{2E_{\nu_e}} \right) / \left( 1 + \frac{m_e}{E_{\nu_e}} \right)^2 \right]^{-1/2}.$$ 

where $m_e$ is the mass of the electron.

For an electron to be detected at the LSND experiment, we must have $E_{e'} \gg m_e$. Using this approximation, we obtain

$$\cos \Theta \approx 1 - \frac{m_e}{E_{e'}} \left( 1 - \frac{E_{e'}}{E_{\nu_e}} \right).$$

A plot of the $\cos \Theta$ distribution, for the $\nu_e$ beam at LSND, is shown in Fig. 1.5.

1.3.4 Interference Term

To calculate the total cross-section, we integrate the differential cross-section, $d\sigma/dy$, over $y$

$$\sigma^{\text{tot}} = \left[ \left( g_i^{\text{cc}} + g_i^{\text{nc}} \right)^2 + \frac{1}{3} \left( g_r^{\text{cc}} + g_r^{\text{nc}} \right)^2 \right] \sigma_0.$$ 

Expanding, we have

$$\sigma^{\text{tot}} = \left[ \left( \left( g_i^{\text{cc}} \right)^2 \right) + \left( 2g_i^{\text{cc}} g_i^{\text{nc}} \right) + \left( \left( g_r^{\text{cc}} \right)^2 + \frac{1}{3} \left( g_r^{\text{nc}} \right)^2 \right) \right] \sigma_0 = \sigma^{\text{CC}} + \sigma^{I} + \sigma^{\text{NC}}.$$

where $\sigma^{\text{CC}}$ ($\sigma^{\text{NC}}$) is the cross-section, had the reaction proceeded only through the CC (NC) channel. $\sigma^{I}$ is a contribution to the cross-section because of interference between the CC and NC channels.
Figure 1.5: The \( \cos \Theta \) distribution.

A dimensionless interference term, \( I \), is defined as

\[
I = \frac{\sigma'}{\sigma_0}.
\]

Expressing \( I \) in terms of \( \sin^2 \theta_W \), we obtain

\[
I = g'^c g'^c = 4 \sin^2 \theta_W - 2.
\]

1.4 A Check of the Standard Model

The \( \nu_e e^- \rightarrow \nu_e e^- \) process is one of the few processes which yields a significant and measurable interference effect between the charged current and neutral current processes. The interference term \( I = g'^c g'^c \) is determined by the value of \( \sin^2 \theta_W \) in the standard model and is negative. This destructive
interference leads to a reduction in the final cross-section by 45% compared to the cross-section had the reaction proceeded only through the charged current channel.

We will measure this interference term and verify whether or not it is negative. We will then compare this measured value to the value predicted by the standard model. This serves as a check of the standard model. Also a value of $\sin^2 \theta_W$, one of the few input parameters to the standard model, can be extracted from the interference term.

The interference effect we mention here is different from the electroweak interference observed in the $e^+e^- \rightarrow \mu^+\mu^-$ reaction which occurs because the annihilation reaction can proceed via the exchange of either a photon or a $Z$ boson. The resulting interference effect has been studied by measuring the forward-backward asymmetry for this reaction.

We are interested in the interference between the $W$ and the $Z$ boson exchange and only a few other processes demonstrate this interference. They are listed below.

1.4.1 The $\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-$ Reaction

This process is shown in Fig. 1.6. The measured cross-section [32] is in agreement with the expected destructive interference, but is also consistent with a purely charged current interaction. Thus the experimental errors are too large to make a quantitative statement on the interference.

1.4.2 The $e^+e^- \rightarrow \gamma \nu\bar{\nu}$ Reaction

This "single photo-production" reaction is shown in Fig. 1.7. Only a single photon is detected and the remaining energy is carried by invisible particles.
All three flavors of neutrinos are produced by the neutral current reaction but the charged current produces only the electron neutrinos. According to the standard model, the NC/CC interference produces a 10 percent reduction in the cross-section determined from Z-exchange only. The OPAL Collaboration has reported 447 single photon candidates [33] near the $Z^0$ resonance. The data is consistent with the SM W contribution but can also be described satisfactorily without any W contribution.

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1.4.3 The $\nu_\mu N \rightarrow \nu_\mu \mu^+ \mu^- N$ Reaction

The $\nu$-trident reaction is characterized by coherent tri-lepton production and no visible hadronic energy. The Feynman diagrams for this process are shown in Fig. 1.8. The CHARM-II group has reported $55 \pm 17$ $\nu$-trident events, in comparison with the SM expected rate of 35 [34].

The CCFR experiment reported a trident signal, after all efficiency corrections, of $37.0 \pm 12.4$ [35]. The predicted number of events from just $W$-exchange is $78.1 \pm 3.9$ and that using the SM $W$ and $Z$ exchange is $45.3 \pm 2.3$. The data rules out at 99% CL the exchange of just the $W$ boson, without any interference.

1.5 Previous Neutrino-Electron Scattering Measurements

This dissertation presents data collected at the LSND experiment. This experiment is located at the Los Alamos Neutron Scattering Center (LANSC), previously known as Los Alamos Meson Physics Facility (LAMPF). Previous neutrino experiments at accelerator facilities were generally conducted with neutrino beams of higher energies than that at LSND. Also the
mechanism of production of these neutrino beams was different. Only muon neutrinos (or muon antineutrinos) were produced in large numbers from pion decay-in-flight (DIF), with energies of the order of a few GeV. CHARM [36], the US-Japan Neutrino Experiment [37] and CHARM-II [38] all reported the $\nu_\mu (\bar{\nu}_\mu) e^- \rightarrow \nu_\mu (\bar{\nu}_\mu) e^-$ scattering cross-sections. Both reactions proceed only through the neutral current channel and do not produce an interference term.

At LSND we do have a small fraction of DIF neutrinos with an average energy of about 100 MeV. However the main source of neutrinos is from $\pi^+$ and $\mu^+$ decay-at-rest (DAR). The average energy of these neutrinos is around 30 MeV. More importantly, the DAR chain produces electron neutrinos.

Only one previous experiment, E225, also located at LAMPF has measured the cross-section for the electron neutrino-electron elastic scattering process. E225 reported a cross-section [39] of

$$\sigma = 9.9 \pm 1.5(\text{stat.}) \pm 1.0(\text{syst.}) \times E_\nu (\text{MeV}) \times 10^{-45}\text{cm}^2$$

and an interference term.

$$I = -1.07 \pm 0.17(\text{stat.}) \pm 0.11(\text{syst.})$$

which compared well with the standard model value of $I = -1.08$. 

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CHAPTER 2

THE LAMPF NEUTRINO BEAM

In this chapter we discuss the production of neutrinos at LSND. A beam of medium energy protons is used to generate the neutrino beam. The proton beam smashes into a target, producing pions. These pions decay to produce muons and neutrinos. The muons also decay producing additional neutrinos.

2.1 The Proton Beam

The Liquid Scintillator Neutrino Detector (LSND) is located at area TA-53 of the Los Alamos National Laboratory (LANL). TA-53 was previously named the Los Alamos Meson Physics Facility (LAMPF) but is now called the Los Alamos Neutron Scattering Center (LANSCE). LANSCE houses a one-half mile long linear accelerator which produces an intense proton beam with energies up to 800 MeV. The typical proton current is 1 mA.

The accelerator uses conventional ion sources for the proton beam. Protons pass through a transition section to a drift tube linear accelerator of the Alvarez type, operating at 201.25 MHz. Protons are accelerated in this section to 50 MeV and then injected into a side coupled linac structure for acceleration to their final energies. The acceleration process is repeated at 120 Hz. During the course of the experiment the final proton beam kinetic energy of 800 MeV was constant to much better than 1%.
Beam spills occur during a 600 \( \mu s \) time window. This beam-gate window is repeated every 8.33 ms (corresponding to the 120 Hz accelerator cycle), as shown in Fig. 2.1. This timing structure is termed the macrostructure of the beam. The proton beam within the beam-gate has a substructure, called the microstructure. Bursts of protons, with a width of 0.20 ns, occur once every 5 ns due to the 201.25 MHz acceleration cycle in the drift tube stage. The microstructure of the beam is also illustrated in Fig. 2.1. The LSND detector operates irrespective of whether the proton beam is present or not. The beam cycle operates so that, on average, the proton beam is present about 6% of the time. The duty ratio is defined as the ratio of the time the beam is present (beam-gate window is "on") to the time the beam is absent (beam-gate window is "off"). For the data presented in this dissertation, we obtain an average duty ratio of 0.062.

2.2 The Beam Stop

The proton beam output of the linear accelerator is transported to a high intensity experimental area (area A) shown in Fig. 2.2. The LSND experiment is located at the end of the beam line in area A. The proton beam passes through two thin targets, A1 and A2, before it reaches A6, the main target for LSND. A1 and A2 are carbon targets, 3 cm and 4 cm thick, respectively, and are located 137 m and 112 m upstream of the detector. Approximately 19% of the proton beam is removed at these upstream targets and the protons arrive at A6 at a reduced energy of 768 MeV.

The A6 target is located 29.8 m upstream of the detector. The plan view of the A6 target box is shown in Fig. 2.3. The proton beam enters
Figure 2.1: The timing pattern of the proton beam showing (a) the microstructure, and (b) the macrostructure.

Figure 2.2: Schematic of the high intensity experimental area.
the A6 window from the left. A schematic view of the A6 target, shown in Fig. 2.4, is better suited to describe its major components. The front end consists of a 30 cm long water target, followed by a decay space of 50 cm. The isotope production stringers are next in line. These are targets that produce radioisotopes for medical uses. The number of these stringers varied during the course of the experiment but all the changes in the target were reproduced in the beam Monte Carlo simulations in order to obtain the correct neutrino fluxes. Last in line is the copper beam stop. All the protons which have survived to this point and all the secondary pions, either produced in the beam stop or entering it, are ultimately absorbed within this beam stop. The A6 target is hermetically sealed due to radiation safety.
considerations and charged particles cannot emerge past the surrounding shielding material. In addition, 8.5 m equivalent of iron shielding is placed between the target and the detector to stop any beam-induced neutrons from entering the detector. Muon and electron type neutrinos arise from pion and muon decay, as discussed in the next section. These neutrinos are essentially the only beam-induced particles which enter the LSND detector.

For the 1996 and 1997 data, the A1 and A2 targets were removed and the A6 target described above was replaced by a new tungsten target.

![Figure 2.4: A schematic diagram of the A6 target.](image)

2.3 The Neutrino Beam

The proton beam interacts inelastically with the material within the A6 target, producing charged pions with energies ranging up to 600 MeV. The ratio of positively charged pions produced to negatively charged pions is approximately 8:1. These pions either decay in flight (DIF) or come to a
stop. The stopping pions either decay at rest (DAR) or are absorbed in the material of the target. Let us follow the $\pi^+$ decay chain.

The dominant decay reaction is

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

(The reaction $\pi^+ \rightarrow e^+ \nu_e$ has a branching ratio of $1.23 \times 10^{-4}$). Only about 3.4% of the $\pi^+$ decay in flight. The remaining $\pi^+$ stop and decay at rest. This decay reaction has a lifetime of 26 ns and is termed the prompt decay. The $\nu_\mu$ energy spectrum for the two body DAR reaction is monoenergetic, as shown in Fig. 6.2. The muon which is produced in the prompt decay comes to rest and then decays via the reaction

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu.$$ 

This reaction has a lifetime of $2.2 \mu$s, much longer than that of the prompt decay. The continuous energy spectra for the $\nu_e$ and $\bar{\nu}_\mu$, produced in the three body decay of the $\mu^+$, are also shown in Fig. 6.2. For the analysis presented in this dissertation, we are interested in neutrinos of the electron type. They are produced with an average energy of 31.7 MeV.

We now look at the $\pi^-$ decay chain. LSND performs a DAR neutrino oscillation search for $\bar{\nu}_e$ in the appearance channel $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ [40]. The $\pi^-$ decay chain produces a major neutrino background for this search. Fortunately this decay chain is greatly suppressed. The water target serves to enhance the $\pi^+$ production relative to the $\pi^-$ production. This is because water has more protons than neutrons, in contrast to high Z materials like copper. All of the $\pi^-$ particles which stop are absorbed in the material of the target. Thus the production of $\bar{\nu}_\mu$ via the reaction

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Figure 2.5: The energy spectra for DAR neutrinos.

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

is due to the small fraction (5\%) of \( \pi^- \) DIF. The \( \mu^- \) particles produced in the above reaction stop and 88\% are absorbed while the remaining 12\% decay at rest. Thus the production of DAR neutrinos from the \( \pi^- \) decay chain is suppressed. In particular, the \( \bar{\nu}_e \) production is suppressed by a factor of \( \sim \frac{1}{3} \times 0.05 \times 0.12 \approx 0.75 \times 10^{-3} \).

The DAR neutrino flux decreases inversely with the square of the distance from the neutrino source. Targets A1 and A2 contribute only 1.4\% to the DAR neutrino flux at the detector because the neutrino production at A1 and A2, combined, is about 25\% that of A6 and they are approximately four times further from the detector than A6. However A1 and A2 contribute a larger fraction of the DIF neutrino flux.
Table 2.1: The Neutrino Fluxes at LSND.

<table>
<thead>
<tr>
<th>Neutrino Flux</th>
<th>Source</th>
<th>Energy Range (MeV)</th>
<th>Relative Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$</td>
<td>$\pi^+$ DAR</td>
<td>29.8</td>
<td>1</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$</td>
<td>$\mu^+$ DAR</td>
<td>0-52.8</td>
<td>1</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>$\mu^+$ DAR</td>
<td>0-52.8</td>
<td>1</td>
</tr>
<tr>
<td>$\bar{\nu}_e$</td>
<td>$\mu^-$ DAR</td>
<td>0-52.8</td>
<td>$0.78 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$</td>
<td>$\pi^+$ DIF</td>
<td>0-300</td>
<td>$0.86 \times 10^{-1}$</td>
</tr>
</tbody>
</table>

It is essential to stress that the DIF neutrino production is small compared to that of the DAR neutrinos. The relative intensities of the various neutrino fluxes, along with their energy ranges, are shown in Table 2.1. For the $\nu_e e^- \rightarrow \nu_e e^-$ elastic scattering process which is discussed in this dissertation, only the DAR neutrino flux is utilized. Hence we will not discuss the details of the DIF flux.

2.4 The Beam Monte Carlo Simulation

A detailed simulation was used to predict neutrino fluxes at the detector [41]. The location of the targets at A1, A2, and A6, along with their respective geometries and material constituents were input to the Monte Carlo simulation.

Measured pion production rates [42] for proton beams of various energies were used by the simulation. In addition, information from a calibration experiment [43] performed at LAMPF. was also used. This experiment measured the yield of muon decays when a proton beam of varying energy was incident on a composite structure of copper and water. These muons arise almost entirely from stopped $\pi^+$ decays since all $\pi^-$ which stop are
absorbed. The target structure was designed to be similar to the A6 water target, the primary source of pion production at LSND.

Several parameters of the beam simulation were renormalized slightly to fit the data from the calibration experiment. This procedure worked well for the positive pion chain which yields the DAR flux. No calibration was possible for the negative pion chain which yields $\bar{\nu}_e$ since over 99.9% of the muons which decay arise from the positive pion chain.

The shape of the energy spectrum for the $\pi^+$ and $\mu^+$ DAR neutrinos is well known and only the absolute amplitude of the DAR neutrino flux is obtained from the simulation. Using the simulation and the calibration experiment, we assign an uncertainty of 7% to the DAR flux calculation. However, there exist uncertainties in both the shape and the normalization of the DIF flux and we estimate a 12% systematic error in its calculation.
CHAPTER 3

THE LSND DETECTOR

The LSND detection apparatus has two components: the detector and the veto shield. The 180 ton detector is a roughly cylindrical tank filled with mineral oil to which a small quantity of scintillator is added. Carbon nuclei and protons in mineral oil, together with electrons, serve as targets for neutrino interactions. The detector medium allows for production of scintillation light in addition to Čerenkov light emitted by highly relativistic charged particles. This light is detected by the photomultiplier tubes which line the inside surface of the tank. The veto shield surrounds the tank and is highly efficient in detecting charged cosmic-ray particles which enter the detector. In this chapter, we will describe the physical structure of each detector component as well as its functional behaviour.

3.1 The Experimental Set-up

The entire LSND apparatus is housed in a tunnel and shielded by an overburden which consists of 2000 gm/cm$^2$ of steel and dirt. The overburden serves to reduce the flux of cosmic-ray particles entering the detector. The overburden, the tunnel and the veto shield used by LSND were actually built for the previous LAMPF neutrino oscillation experiment, E645. Fig. 3.1 shows a plan view of the experimental set-up. The proton beam is incident on the beam stop from the left. The neutrinos produced at the beam stop travel unimpeded and can produce interactions within our detector.
Figure 3.1: A cross sectional view of the LSND experimental set-up.

The tunnel is semi-cylindrical, 30 m long and 14 m in diameter, with walls of corrugated steel. It is located at a lower height than the A6 beam stop. When viewed from above, the tunnel is also off-center from the proton beam axis. A line connecting the center of the beam stop to the center of the detector bends downward by 9.4° when projected onto a vertical plane, and bends to the left of the proton beam axis by 7.6° when projected onto a horizontal plane. Stacked at the upstream end of the tunnel are iron slabs which form a 2 m thick wall, serving to shield against beam-related neutrons. This is the closed end of the tunnel. At the downstream end, there is an 8 m long water plug which reduces the cosmic-ray background entering the detector from the open end of the tunnel.
3.2 The Detector

The detector was designed to track the path of relativistic charged particles and to measure the energy deposited by them as they traversed the detector medium. Both these goals were met, as described below, using a simple design of a tank filled with liquid.

The detector consists of a roughly cylindrical steel tank, 8.75 m long with a diameter of 5.72 m, as shown schematically in Fig. 3.2. Its central axis is roughly parallel to the neutrino beam. Both the top and the bottom of the tank are flat. The flat base rests on steel shielding, extending over the entire length and width of the tank. The detector is almost fully enclosed in a veto shield, to be described in the next section. As mentioned earlier, additional shielding is provided by the tunnel and the overburden.

![Figure 3.2: A schematic diagram of the detector tank showing the placement of PMTs.](image)

Only high energy cosmic-ray muons penetrate through the shielding and either enter the tank or interact in its vicinity. Some undergo nuclear deep inelastic scattering and knock out neutrons. Thus we have a source of
cosmic-ray neutrons entering the detector. A fraction of the muons may enter the detector, stop inside it and then decay to produce Michel electrons (or positrons). For energy ranges of interest to this dissertation, this sample of Michel electrons is the dominant source of electrons in the detector. It is a clean sample because, prior to the electron detection, we detect the muon both in the veto and the tank. For these reasons, this sample is very useful for a number of studies we will conduct later.

The interior of the tank is uniformly mounted with 1220 photomultiplier tubes (PMTs), which face inward. These PMTs are 8 inches in diameter and are of the type R1408 manufactured by Hamamatsu. The number of PMTs was chosen to achieve a 25% PMT coverage over the total internal area of the tank walls. The fast-timing PMTs were built to a special contract using low radioactivity glass. The PMTs were mounted on metal frames and the photocathode surface protruded inward approximately 25 cm from the tank walls.

The tank was initially filled with about 50,000 gallons of pure mineral oil. Chemically, mineral oil is composed of linear chain hydrocarbon molecules \(C_nH_{2n+2}\) where \(n\) varies from 22 to 26. Relativistic charged particles travelling through mineral oil produce Čerenkov light.

Čerenkov light is emitted in a cone around the direction of travel of the particle. The angle \(\theta\) of the cone, measured from the direction of travel, is fixed by the refractive index \(\eta\) of the medium and the velocity \(v\) of the particle.

\[
\cos \theta = \frac{1}{\beta \eta}.
\]

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For mineral oil, the refractive index is 1.47. Hence \( \cos \theta = 0.68 \) and \( \theta = 47.1^\circ \) for highly relativistic \((\beta \sim 1)\) particles. The velocity, \( \beta_0 \), is the threshold Čerenkov velocity, below which particles do not produce any Čerenkov light. It is given by

\[
\beta_0 = \frac{1}{\eta}.
\]

There are several advantages in using mineral oil. The oil used had a radioactive component below one part in \(10^{12}\). It was non-toxic and retained a stable light attenuation length as it was not exposed to oxygen. It had a high refractive index of 1.47, which increased the Čerenkov light generated by a relativistic electron by a factor of 1.57 compared to water. Finally a mineral-oil-based scintillator could be dissolved in it to enhance the light production of charged particles.

Whenever a charged particle traverses through a scintillator medium, it produces light via fluorescence. This scintillation light is proportional to the energy loss of the charged particle as it travels through the medium. It is isotropic in space and there is no velocity or energy threshold for its production. Thus heavier particles like protons and slower moving muons will generate scintillation light, even if they do not produce Čerenkov light.

Initially, some data was collected when the tank was filled with just pure mineral oil. For this data, a typical Michel electron produced a very distinct ring of hit PMTs, obtained when a cone of Čerenkov light was projected onto the tank walls. Slowly a mineral-oil-based scintillator b-PBD (butyl-phenyl-biphenyl-oxydiazole, CHNO) was added, making the Čerenkov rings less visible because an increasing amount of isotropic scintillation light was
also being produced. However the Čerenkov rings could still be detected by
our sophisticated event reconstruction software, discussed in Chapter 5.

Before the construction of the detector, extensive testing of various mineral-
oil-based scintillators was performed using a beam of positrons and protons,
produced in a test channel at LAMPF [44]. A concentration of 0.031 g/l of
b-PBD in mineral oil was determined to be optimal for the detector. Thus
a total of 6 kg of b-PBD was added to the mineral oil in the tank, over a
two week period, in order to obtain the desired concentration of scintillator
within the detector. The liquid used in LSND, hence, is a dilute scintillator.

A fraction of the Čerenkov light generated by a relativistic charged par-
ticle is absorbed by the scintillator and then re-emitted as isotropic scin-
tillation light. This component of Čerenkov light thus gets added to the
scintillation light. The component of Čerenkov light that is not absorbed
and continues to propagate along the Čerenkov cone will be termed "direct"
Čerenkov light. For a sample of Michel electrons which are highly relativistic
particles, the ratio of the number of photoelectrons generated in the PMTs
from isotropic scintillation light to that from direct Čerenkov light is deter-
mined to be about 5 to 1.

In Chapter 5, we will discuss the event reconstruction procedure which
allows us to determine the location of particles within the detector. For
highly relativistic particles, we can also obtain their direction of propagation
by locating the cone of Čerenkov light that they emit. Let us illustrate the
presence of this Čerenkov cone of light.
For this purpose, we will use a sample of Michel electrons whose position and direction information has been determined using the event reconstruction procedure. For a single Michel electron, imagine that we are located at its origin and are looking down its direction of propagation. We define $\theta$ as the angle we would have to turn to look directly at one of the detector PMTs. We record $\cos \theta$ and the charge in photoelectrons, if any, for that PMT and for all other detector PMTs. We then plot, in Fig. 3.3, the charge weighted PMT hits versus $\cos \theta$, averaged for all Michel electrons within the sample. This plot shows a clear peak due to direct Čerenkov light at $\cos \theta \sim 0.68$ and an approximately isotropic (flat) distribution due to scintillation light. We thus display the production of both types of light within the LSND detector.

Above, we have mentioned that the detector performs the function of tracking relativistic charged particles. In Chapter 5, we will also discuss how the detector serves as a calorimetric device for measuring the energy of charged particles that are contained within the detector.

### 3.3 The Veto Shield

The veto shield used by LSND serves two functions. First its active component serves as an anticounter for charged particles entering the detector from outside. Second it provides additional passive shielding to the detector. As mentioned earlier, the veto shield was constructed for and used by the previous neutrino oscillation experiment at LAMPF, E645. The LSU group worked on refurbishing this veto shield for the LSND experiment.

The veto shield almost fully encloses the detector except for the support structure on the floor on which the detector rests. This support structure is
Figure 3.3: Angular distribution of PMTs, weighted by pulse heights, with respect to the fitted Michel electron direction. Data (solid) is compared to detector Monte Carlo simulation (dashed). The smooth curve is fit to a constant, P4, plus a gaussian with a mean P2, sigma P3, and renormalization P1.

A concrete pad, covered by 6-in. thick steel blocks. The cracks between these blocks were filled with steel shot. Thus there is adequate passive shielding at the bottom but there is no active shielding.

The veto shield is a cylindrical steel structure with two closed ends and a truncated bottom. It has a diameter of 6.75 m and a length of 10.1 m. A cross sectional view of the shield, normal to the detector axis, is shown in Fig. 3.4. The veto shield comprises of two structurally independent parts.
The upstream end, which is painted blue and called the blue wall, is one independent unit. The cylindrical shell is fused with the other end and together they form the second unit. This unit is painted red and its end wall, which resides downstream, is called the red wall. The neutrino tunnel has rail tracks which extend beyond its open end. Both these units are equipped with wheels and can be moved along the tracks. As shown in the cross sectional view of Fig. 3.4, any particle entering the veto shield from outside first passes through the active component of the veto shield.

Figure 3.4: A cross sectional view of the veto shield.
3.3.1 The Active Component

The active component of the shield consists of an outer shell filled with about 10,000 gallons of liquid scintillator. BC517P, which is a mixture of 5% pseudocumene in mineral oil, was used as the liquid scintillator. The scintillator is viewed from the outside through port-holes by a total of 292 uniformly spaced PMTs (46 each on the end walls and 200 on the cylindrical surface). Five inch diameter photomultiplier tubes of the type 9870B, manufactured by EMI, were used for this purpose.

A charged particle passing through the liquid scintillator emits light that is detected by the array of PMTs which line the outer wall and look inward. The inner wall of the shell enclosing the scintillator is painted white to minimize the absorption of light at that surface. Thus, barring inefficiency in the system, any charged particle entering the active region of the veto shield is tagged by the hits in the veto PMTs.

3.3.2 The Passive Component

The passive shield is a layer of lead shots 18 cm thick, filled with a packing fraction of 0.7. It is helpful in stopping neutral particles like photons and neutrons from entering the detector. These neutral particle are not tagged as they pass through the active region of the veto shield.

If photons enter the detector, they can be mistaken for electron events, creating a source of background. Such photons are generally cosmic-ray muon induced. Either the muons bremsstrahlung in the overburden or they stop and decay in the overburden generating Michel electrons which subsequently bremsstrahlung to produce the photons. The passive shielding was designed to reduce this photon background.
Note that the passive shielding is located to the inside of the active region. If a cosmic-ray muon were to stop and decay in the lead of the passive shielding and produce a Bremsstrahlung photon, this photon is tagged by the muon passing through the active region.

3.3.3 The Crack Counters and the Bottom-edge Counters

As mentioned earlier the veto shield is comprised of two separate units. The blue wall is moved in to cover the open end of the other cylindrical shell structure. As a consequence of this, the region in the veto shield at the intersection of these two structures is susceptible to penetration by cosmic-ray muons. This weakness is of particular concern at the top of the veto shield as cosmic-ray muons are predominantly directed downward and some might pass through this region undetected and then enter the tank.

To avoid this problem, plastic scintillation veto counters, which we term "crack counters", were installed to completely cover the top half of the weak region. These counters were built and installed by the LSU group. The dimensions of these crack counters are shown in Fig. 3.5. The central rectangular plastic scintillation region is flanked by two triangular light guides, with a phototube (PMT) located at each extremity. There are twelve such crack counters.

Also as mentioned earlier, there is no active shielding at the bottom of the detector and the truncated cylindrical shell of the veto does not quite extend all the way down to the floor. This leaves a gap in the active shielding through which some cosmic-ray muons can enter the detector undetected. To reduce this background, the LSU group installed "bottom-edge counters".
These sixteen counters were wedged between the veto and the walls of the tunnel, serving to extend the coverage of the active region down to the floor. They are similar to the crack counters, only smaller on average. Their mean dimensions are 48" × 20".

For these plastic scintillation counters, when a charged particle passes through the scintillator, it produces light which is collected by the two light guides and transmitted to their respective PMTs. The PMT pulse, generated by this light, is fed into an amplifier and then into a discriminator. If this amplified pulse is above a certain preset threshold, the discriminator is triggered. In order to discriminate against the accidental firing of a PMT, we require that both the PMTs located at either ends of the counter produce pulses above the discriminator threshold that are coincidental in time. Thus
the two respective discriminator pulses are fed into a coincidence circuit, which determines if the counter has recorded a legitimate hit. If any one of the sixteen bottom-edge counters produces a hit, the timing and pulse height information from each of these counters is recorded into the data stream, to be used for later analysis. The same procedure is followed for recording crack counter hits, but additionally, the crack counter hits are also used along with the veto tube hits to make triggering decisions. The working of the trigger and the data acquisition system (DAQ) is discussed in the next chapter.

The author worked on producing, calibrating and installing the bottom-edge counters. He also assembled the above mentioned NIM electronics for these counters. In addition to the veto system described here, in early 1996 the author helped install a set of “upstream veto counters”. This final addition of scintillation counters was located in front of the blue wall of the veto shield. These counters augmented the bottom-edge counters and differed only in the sense that they were smaller and were fitted with just one light guide and one corresponding PMT.
CHAPTER 4

DATA ACQUISITION AT LSND

In this chapter we describe the LSND data acquisition system. We begin by discussing the electronics for each channel of data acquisition. We then describe the triggering system which allows us to choose and record only those events of interest to the experiment.

4.1 Electronics

The LSND experiment has 1220 detector photomultiplier (PMT) tubes. 292 PMTs in the main veto shield, 24 PMTs on the crack counters and 32 PMTs on the bottom-edge counters. Each PMT is a separate channel for the data acquisition (DAQ) system.

Whenever a charged particle traverses the detector medium, it produces light within the detector. This light, if it travels through the medium and arrives at a PMT, will, with a certain probability, generate one or more electrons at the photocathode surface of the PMT. These photoelectrons yield a phototube charge, Q, proportional to the light incident at the photocathode surface. In addition to the charge, the arrival time, T, of the PMT pulse is also recorded.

Thus each hit PMT channel yields a charge, Q, and a time, T. One has to collect this information from all the hit PMTs and from that assemble the actual event. This procedure, called the event reconstruction, determines

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the mid-point of the track generated by the particle within the detector, the
direction of this track and the energy of the particle. The event reconstruc-
tion procedure is described in the next chapter. Here, we briefly describe the
electronics used to extract the Q and T information from the PMT pulse.

![Diagram of electronics for a single PMT channel.](image)

**Figure 4.1:** Electronics for a single PMT channel.

Fig. 4.1 shows the electronics for a single PMT channel. The amplified
PMT pulse is fed into a charge capacitor which acts as an integrator. The
voltage $V_q$ from the integrator yields a measure of the phototube charge, $Q$,
and is shown as the sixth listed item in Fig. 4.2. The amplified PMT pulse
is also sent to a discriminator. If this pulse is above a certain threshold, the
discriminator generates a square pulse, also shown in Fig. 4.2.
Figure 4.2: The charge and the timing information from a single PMT channel.

This discriminator pulse initiates a linear ramp, $V_t$, shown as the eighth listed item in Fig. 4.2. The voltage $V_t$ is used to determine the timing of the hit PMT. Both $V_q$ and $V_t$ are input into separate 8-bit Flash Analog to Digital Converters (FADCs) which record these voltages every 100 ns. corresponding to each tick of a 10 MHz clock. This clock is at the heart of the data acquisition system and governs not only the digitization but also when the data is written in and out of memory chips.
The discriminator pulse from each PMT channel is also directed into a summing device. The total number of hit PMTs are summed, separately for the tank and the veto. These sums are used in the trigger system which was designed to record interesting events while reducing the number of events due to cosmic-ray interactions. The trigger is described in the next section.

At each PMT channel, \( V_q \) is digitized every 100 ns and written to a Random Access Memory (RAM) allocated solely to that channel. The memory address of the digitized value is conveniently provided by the 11 least significant bits of the clock time at which \( V_q \) was recorded. This address is termed "the time stamp address" (TSA). It should be noted that we keep recording this digitized information irrespective of whether the PMT was hit or not. Thus the value of \( V_q \) recorded just before the PMT was hit serves as a baseline value and the voltage above this value is a measure of the PMT charge \( Q \). This dynamic approach allows for continuous data acquisition with no dead-time due to resetting of voltages.

The timing pulse, \( V_t \), is also flash digitized every 100 ns and each value is stored within the RAM, beside the corresponding value for \( V_q \). As seen in Fig. 4.2, the discriminator is triggered by the PMT pulse and the square pulse is present until the second tick of the 10 MHz clock after the PMT was hit. As a response to this discriminator pulse, a linear ramp is generated and two digitized values of \( V_t \) are recorded on this ramp. Observing the \( V_t \) plot in Fig. 4.2, one can see that the time of the PMT pulse can be obtained by extrapolating back from the two \( V_t \) values. We locate the intersection of the line joining these two values with the baseline. This intersection point yields
what we will term the "fine time" of the phototube pulse. Also once initiated, this timing ramp is unaffected by the arrival of subsequent phototube pulses for 200 to 300 ns, depending on the phase of the initial hit with respect to the 10 MHz clock. Thus if a PMT is hit twice, in close succession, then the second hit will not record any fine time information.

Each channel RAM collects 8-bit Q and T data every 100 ns and, because of the 16 bit x 2048 memory of the chip, contains a 204.8 μs history of activity for that channel. If a trigger readout order is broadcast to a PMT channel, data is transferred from the RAM to a FIFO (first-in-first-out) buffer, an 18 bit x 2048 memory chip allocated solely to serve that PMT channel.

Electronic devices termed "QT cards" house the digitized fine time and charge information from individual PMT channels. Each QT card accepts information from 8 PMT channels. The 10 MHz clock arrives at each QT card and is accurate to a few nanoseconds. This provides a "course time" for the events. 16 QT cards, a receiver-trigger interface card, and a crate channel summation card are grouped together within a VME crate called a "QT crate". Each crate is also equipped with a monoboard computer which assembles an event at the crate level and on receipt of a broadcast trigger signal transmits this event to a central SGI multiprocessor.

4.2 Trigger
As mentioned earlier, for each PMT channel the discriminator generates a logic signal in response to a PMT pulse. This signal remains asserted for two consecutive clock ticks after the arrival of the PMT pulse. We obtain an instantaneous count of hit PMTs by digitally summing these logic signals
Table 4.1: The Trigger Thresholds.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Activity</td>
<td>$D \geq 18$ or $V \geq 6$</td>
<td>$D \geq 18$ or $V \geq 6$</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>$D \geq 21$ and $V &lt; 4$</td>
<td>$D \geq 21$ and $V &lt; 4$</td>
</tr>
<tr>
<td>Primary</td>
<td>none</td>
<td>$D \geq 75$ and $V &lt; 4$</td>
</tr>
<tr>
<td>Primary, $\gamma$ window</td>
<td>$D \geq 100$ and $V &lt; 4$</td>
<td>$D \geq 150$ and $V &lt; 4$</td>
</tr>
<tr>
<td>Primary, $\gamma$, look-back</td>
<td>none</td>
<td>$D \geq 150$ and $V &lt; 4$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$D \geq 300$ and $V &lt; 4$</td>
</tr>
</tbody>
</table>

at the crate level at each tick of the binary clock. Appropriate crates are then summed to obtain a global count of the PMT hits, separately, for the veto and the detector. The sums, thus obtained, are then compared to preset values assigned for the veto and the detector. These preset values serve as veto or detector thresholds where we write an event into the data stream if it meets or surpasses the threshold requirement.

At LSND we categorize an event depending on the number of detector ($D$) and veto ($V$) hits it produces. The different event categories, together with their detector and veto threshold requirements, are illustrated in Table 4.1. A triggering algorithm decides whether or not to select or, as we will explain later, “broadcast” an event. Each event category has a different broadcast code associated with it. We will describe the different events types and their requirements below. Notice that the threshold values changed through the years and additions were made to the types of events because, as the collaboration gathered more data, more refined triggering schemes were employed.
4.2.1 Event Categories

Cosmic-ray muons produce the vast majority of interactions within the LSND detector. We require that for any event to be broadcast, it must produce less than four hits in the veto. This severely limits the cosmic-ray muons from being included in the data stream. Only about two in every thousand cosmic-ray muons produce fewer veto hits than this threshold. Also the cosmic-ray muons which enter the detector may stop within the tank and then decay to produce Michel electrons. We require that for any activity which produces greater than five veto hits, we do not broadcast a subsequent event if it lies within 15.2 \( \mu s \) of the original activity. The lifetime for muon decay is 2.15 \( \mu s \) within our detector. Hence the 15.2 \( \mu s \) "veto hold" requirement prevents the writing out of Michel electrons for most cosmic-ray muon decays. Out of a thousand muons which stop and decay in our detector, only one produces a Michel electron 15.2 \( \mu s \) after its decay, which is then broadcast as a primary event. However, due to the high rate of cosmic-ray muons and despite the veto hold requirement, we record one Michel electron every 10 seconds, compared to the rate of a few (~10-15) neutrino events per day.

At LSND, we define a "primary event" as an interaction that produces 100 or more detector PMT hits. This corresponds to \( \sim 4 \) MeV in electron energy within the tank. As mentioned above, we have to keep a record of all activities prior to the primary to decide whether or not to broadcast the primary. In addition to the primary, we write out activities which lie within 51.2 \( \mu s \) prior to it. If there are fewer than five, these "past activities" are

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all broadcast in conjunction with the primary event. For the rare cases in which there are five or more activities, the four closest in time to the primary event are broadcast. Also for the DAR oscillation search, one has to detect a 2.2 MeV gamma after the primary event, produced via the neutron capture reaction,

\[ n + p \rightarrow d + \gamma. \]

We expect a neutron capture lifetime of 186 \( \mu s \) at LSND. In order to detect the gamma, one has to lower the detector threshold after each primary event. This is achieved by what we term “opening a \( \gamma \) window” in the data stream. For a period of 1 ms after the occurrence of a primary event, any event with detector hits, \( 21 \leq D < 100 \), is broadcast as a \( \gamma \) candidate.

For data collected from 1995 onwards, new detector thresholds were adopted to broadcast “\( \beta \) events”. As the name suggests, these are beta decay events, produced mostly due to cosmic-ray interactions. They typically have lower energies than neutrino induced events and have a trigger requirement of 75-150 detector PMT hits. The primary threshold was correspondingly raised to 150 detector hits. The differences between the \( \beta \) and the primary events are that for the \( \beta \) events no past activities are broadcast and no \( \gamma \) window is opened.

Also starting from 1995, look-back events were introduced into the data stream. Every PMT hit that occurred in the intervals 0-3 and 3-6 \( \mu s \) prior to certain selected primary events was recorded for both the detector and the veto shield. Hits in each interval were loosely termed as a “look-back event”. Previously, due to the existence of detector and veto thresholds for
activities, events prior to the primary with hits below these requirements would go unrecorded. The look-back events were introduced to ensure that the primary events were not Michel electrons ensuing from muons that did not meet the activity threshold requirements either in the tank or the veto. Here, muons produced by interactions of DIF neutrinos are of particular interest, especially when neutrons are also produced,

\[ \bar{\nu}_\mu + p \rightarrow \mu^+ + n \]

\[ \nu_\mu + ^{12}C \rightarrow \mu^- + X. \]

If the muon produces fewer hits than the detector activity threshold, it will go undetected and subsequently produce a Michel electron. This Michel electron might then be misidentified as a DAR oscillation candidate if the accompanying neutron produces a gamma signature event [40]. With the look-back information, we can check for detector hits prior to a primary event in order to identify the muon.

The author also used the veto look-back information to identify cosmic-ray muons which are not recorded as activities because they produce fewer than six veto PMT hits. This helped reduce the cosmic-ray background for the \( \nu_e e^- \) elastic scattering reaction and will be discussed later.

The look-back scheme causes a lot of data to be recorded and it was decided that only a subset of primary events which satisfy additional criteria would have the two look-back events broadcast along with the primary. The hit requirements for primary events with look-back are listed in Table 4.1. In addition, for the 1995 run, we required the selected primary event to have

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no activities in a 35 $\mu$s interval prior to it in order for it to have a look-back. This requirement was changed to 20 $\mu$s from the year 1996 onward.

4.2.2 Trigger Hardware and Software

Let us now discuss the trigger hardware and the actual operation of the trigger. The trigger module is also enclosed in a VME crate and consists of a global digital sum card, a comparator, a FIFO memory card, a broadcast card and two computer monoboards referred to as master and satellite. The global PMT sums from the detector and the veto are interrogated by a comparator system. There exist preset values for the detector ($D_n$) and the veto ($V_n$). If a global sum exceeds a preset value, the corresponding comparator level is set.

If a primary or an activity comparator is set, data describing that event is written to the trigger FIFO. The trigger operates independently of the state of the proton beam and tags individual events as in-time or out-of-time with the proton macropulse. There is a FIFO memory bit called “H+” associated with this tag and H+ “on” signifies that the event was in-time with the proton macropulse. The FIFO also contains data from the comparator bits, the laser bit, the bottom-edge veto bit and the pre-beam timing signal.

The trigger master monoboard polls this FIFO and, whenever data is present, subjects the FIFO data to the conditions for data selection. The flow chart of the software handling data selection is shown in Fig. 4.3. Six consecutive time stamp addresses (TSAs) spanning a time period of 0.5 $\mu$s are bunched together and termed as a “molecule”. Henceforth, whenever we speak of an event we will be referring to the composite set of data contained within the molecule. The master monoboard software first decides whether
or not the current event lies within a 15.2 µs veto hold period, as described earlier. If it does not, the event is selected and categorized depending upon the number of hit detector PMTs. The comparator levels used in the flow chart are obtained from Table 4.1. For example, V1 asserted corresponds to \( V \geq 6 \) veto hits for any one of the six TSAs within the event. If an event is selected, its six TSAs are broadcast to each of the 13 QT crates.
For the individual PMT channel this broadcast prompts the transfer of data from the channel RAM to the channel FIFO. With the requisite data in the channel FIFOs, the QT crate monoboard begins transferring the data from each of its associated channel FIFOs to its memory. This process continues until all channel FIFOs are empty. Then the sub-event is processed at the crate level and transmitted to the central SGI multiprocessor via the ethernet. The multiprocessor contains eight independent processors. An event is built in one processor and a second processor distributes this event to the remaining six processors that were used exclusively for on-line event reconstruction.
CHAPTER 5

EVENT RECONSTRUCTION

In this chapter we describe the event reconstruction procedure. Here, the raw data from each PMT channel is processed into event information that can be utilized by our analysis.

5.1 Data Readout

When the QT data arrives at the SGI multiprocessor, it is first translated from raw data into compact data. Each compact data block consists of a header followed by a list of hit tubes and their QT information.

The header includes information which allows the event builder to verify proper assembly of the event fragments. LSND employs a laser calibration system which is discussed in the next section. The header includes the calibration data file identifier for the event. It also includes the number of TSAs for the event, the number of hit detector PMTs with fine time and the number for which no fine time information was recorded. Information about each hit PMT is arranged in a block of four variables: the tube number, its time, charge and saturation information. This information is listed for all hit PMTs following the header. The compact data bank is stored in CERN library ZEBRA format and is used for the online event reconstruction procedure [45].
Table 5.1: Coordinates of the LUDOX Bulbs.

<table>
<thead>
<tr>
<th>Flask</th>
<th>x (cm)</th>
<th>y (cm)</th>
<th>z (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-36.5</td>
<td>27.3</td>
<td>-143.5</td>
</tr>
<tr>
<td>2</td>
<td>35.2</td>
<td>28.6</td>
<td>1.3</td>
</tr>
<tr>
<td>3</td>
<td>-35.2</td>
<td>27.9</td>
<td>221.6</td>
</tr>
</tbody>
</table>

5.2 Laser Calibration

Individual channel calibration for the detector PMTs was performed using a pulsed laser calibration system. This system consists of three 500 ml optical flasks connected to an $\mathrm{N_2}$-dye laser via fiber-optic cables. The location of these flasks within the detector is given in Table 5.1. The Z axis is defined along the central axis of the detector and the Y axis points upward.

The flasks are glass bulbs filled with LUDOX, an aqueous colloidal solution of silica. A cable from the laser enters each flask from the top and is terminated just above the center of the flask. This set-up generates flashes of light which are approximately isotropic.

The amplitude of the laser pulses are remotely controlled and varied so as to achieve calibration over a large energy range. A switching mechanism directs each laser pulse to a particular flask. This is sequentially rotated to all three flasks and the entire cycle is continuously repeated. The laser pulses are spaced randomly in time and the laser cycle operates asynchronously with respect to the accelerator cycle. Each laser event is tagged as a special event to distinguish it from data events. Due to these features, laser events can serve as a random strobe for the data acquisition system.
The average rate of laser events is maintained at about 0.1 Hz. The main purpose of the laser is to serve as a calibration device for the detector PMTs. The gain and time responses of the individual PMTs and their associated electronics, in general, vary from channel to channel and with time. Thus calibration was performed periodically to adjust for these changes.

The PMT gain is defined as the total charge output generated by a phototube in response to a single photoelectron illumination. Low intensity laser light was used to study this response for individual PMTs. Gain calibration was obtained for the laser data by fitting the resolved single photoelectron peak for each PMT.

Two types of timing corrections were required. The first was the timing offset wherein the tube times obtained from high intensity laser runs were used to correct for any relative offsets, in time, between the PMT channels. The position of each laser flask is fixed for the experiment and after accounting for the time of flight for light to travel from the flask to a particular PMT one could calculate the time offset for that PMT channel.

The second correction is termed the "time slewing" correction. This effect arises because of the different times required by PMT pulses of varying magnitudes to reach the discriminator triggering threshold. For example a small PMT pulse takes longer than a large pulse to trigger the discriminator. The functional dependence of the time slewing correction is assumed to be $1/\sqrt{q}$, uniformly, for all PMTs. where $q$ is the PMT pulse height. The mean effect was calculated using the collective information from all hit detector PMTs for low intensity laser data.
These timing corrections resulted in times accurate to ~ 1 ns for the individual PMT channels. Henceforth whenever we refer to individual PMT times it should be understood that these reflect the final values after all timing corrections were made. The robust nature of these calibration corrections is apparent when we notice that even though we repeated the calibration measurements periodically, the corrections were stable throughout the data-taking period.

5.3 Event Reconstruction

The event reconstruction algorithm proceeds in the following four stages:

1. Determination of $\sigma_T$.

2. Fast fit.

3. Full fit, and

4. Angle fit.

This algorithm was initially developed using a sample of simulated Michel electrons. A number of parameters were tuned using this sample so as to optimize the results from each stage of the reconstruction procedure.

5.3.1 Determination of $\sigma_T$

For each event $\sigma_T$ is a measure of the spread in the time distribution of the PMTs. One first calculates the mean time $\bar{t}$, for all hit detector PMTs. Then, $\sigma_T$ is the standard deviation from the mean PMT time:

$$\sigma_T = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (t_i - \bar{t})^2}.$$
Here, $t_i$ is the time of phototube $i$ and $n$ is the total number of hit PMTs with fine time. A large $\sigma_T$ signifies that the event is probably a result of multiple interactions within the tank. If $\sigma_T > 100$ ns, no further reconstruction is performed and the event is tagged as a multiple event candidate.

5.3.2 The Fast Fit

This procedure gives a fast and rough estimate of the time of occurrence of the event and its position within the detector. The first step is to adjust the time of all PMTs with a pulse height smaller than four photoelectrons. The time for each of these PMTs is set to the earliest PMT time of it or one of its four nearest neighbours. The use of this procedure improved the event reconstruction appreciably. Then the mean hit time, $\bar{t}$, is recalculated ignoring hits for which $t_i > \bar{t} + 100$ ns. The initial event time is estimated as the mean time less 11 ns.

$$t_0 = \bar{t} - 11.$$

For each detector PMT, if its time, $t_i$, is greater than the initial estimate of the event time, a correction is made to its geometrical position. The PMT position is shifted inward along the direction normal to the tank surface, by a distance of $v(t_i - t_0)$ where $v = 20$ cm/ns is the velocity of light in mineral oil. This displacement is limited to a maximum of 4.5 m. If $t_i < t_0$ no correction is made to the geometrical position of the PMT. The mean corrected position of the PMTs, with each PMT position weighted by the square of its pulse height, serves as an initial guess for the position of the event.
Using this initial position, the event time is recalculated as the average value of the corrected PMT times, weighted by the square of the pulse heights. The corrected time for PMT $i$ is defined as $(t_i - r_i/v)$, where $r_i$ is the distance from the event vertex to phototube $i$. Here, phototubes with $t_i - t_0 > 17.5$ ns or $t_i - t_0 < -8.75$ ns were ignored. Next the event position is recalculated as before, and this cycle of obtaining time and then position is repeated thrice. The final vertex position of the event along with its estimated time of occurrence are fed into the next stage of the reconstruction algorithm.

### 5.3.3 The Full Fit

A $\chi_r$ function is defined as

$$
\chi_r = \sum_i (t_i - r_i/v - t_0)^2 W_i/(Q - 6),
$$

where $Q$ is the total number of photoelectrons collected by the detector PMTs for the event and the weight, $W_i$, is the pulse height of phototube $i$ if its corrected time, $(t_i - r_i/v)$, is earlier than the event time, $t_0$. Else $W_i$ is 0.04 times the pulse height.

The quantity $\chi_r$ is then minimized using a grid in space and time. The 4-vector $(x, y, z, vt)$ is used to represent the event vertex and its time of occurrence, where the velocity of light in mineral oil is used to convert $t$ into units of length. An iteration is performed wherein the 4-vector vertex is varied in steps of 25 cm over the space-time grid about the initial value obtained from the fast fit. The point on the grid that gives the minimum value of $\chi_r$ is chosen. The grid step size is then decreased to 10 cm and ultimately to 4 cm and we select the 4-vector vertex which minimizes $\chi_r$. This value of $\chi_r$ is stored and used as a measure of goodness of the event vertex fit.
For DAR neutrino interactions which produce an electron in the detector, we observe a single short track of light. The typical track length of about 15 cm is very small compared to the dimensions of the detector. On the other hand a neutron, being a neutral particle, is detected differently within the detector. It cannot produce any light of its own and must knock out one or more protons within the detector medium. The protons are then detected as they generate light tracks at their point of production. If two or more protons are produced, the \( \chi^2 \) value for the fitted event tends to be higher because the full fit procedure was optimized for single track events. This effect can be utilized to help distinguish electrons from neutrons.

It should be mentioned that for an electron the full fit procedure locates the event position vertex at the mid-point of its light track. This fitted position is different from the creation point of the electron. For short tracks the difference between these positions is small. Also knowing the direction of travel of the electron and its energy, one can backtrack from the fitted vertex to arrive at the origin of the electron.

5.3.4 The Angle Fit

As mentioned in Chapter 3, a relativistic charged particle emits Čerenkov light along its direction of travel in the form of a cone of light. For highly relativistic particles in mineral oil, this cone subtends an angle of 47.1° with respect to the direction of travel. Thus once we locate the vertex position for the event using the full fit procedure, we can look for the Čerenkov cone to determine its direction of travel.
The angle fitting algorithm, designed to locate the Čerenkov cone, is described below. We use the fact that Čerenkov light is promptly emitted by a particle whereas the emission of scintillation light, because of its production mechanism via fluorescence, is delayed.

A “prompt hit” is defined as a PMT hit that occurred within 4 ns of the event time. Mathematically, the difference between the corrected PMT time, \((t_i - r_i/v)\), and the event reconstruction time, \(t_0\), must be less than 4 ns for a hit to be classified as a prompt hit. The angle fitting routine uses only PMTs with prompt hits.

To determine the event direction, we first define 26 spatial directions which are uniform in \(4\pi\). The angle fitting routine picks out one direction for further investigation. A variable, \(\chi_1\), is defined as

\[
\chi_1 = \sum_i \frac{(\theta_i - 47.14^\circ)^2}{2 \times 12^\circ} W_i Q_{exp} \left( \frac{r_i}{14.9} \right),
\]

where \(\theta_i\) is the angle, in degrees, between this direction and the line connecting the event vertex to phototube \(i\). \(W_i\) is the pulse height of phototube \(i\). and \(r_i\) is the distance, in meters, from the event vertex to phototube \(i\). The value of \(\chi_1\) is calculated for the chosen direction and stored.

The ratio

\[
\frac{(\theta_i - 47.1^\circ)^2}{2 \times 12^\circ}
\]

is limited to 0.894 except in two regions, \(0.052 < \cos \theta_i < 0.309\) and \(\cos \theta_i > 0.927\), where it is set to 1.044.

A fine net is then set up around this direction, in steps of 0.75 radians along the polar and azimuthal directions. The angle fitting algorithm then
proceeds to determine a local minimum in the $\chi_1$ variable for the different directions along the net. If a minimum is found, its value replaces the stored $\chi_1$ value. The direction yielding the minimum also supplants the initial chosen direction as a candidate for the event direction.

This procedure is repeated for the remaining 25 directions. The direction that provides the smallest of the 26 $\chi_1$ values is chosen as the event direction. A new variable, $\chi_a$, is constructed using the smallest $\chi_1$ value:

$$\chi_a = \frac{1 + d/4}{2Q_{\text{prompt}}(Q_{\text{prompt}} - 2)} \chi_{1\text{min}},$$

where $d$ is the distance, in meters, from the event vertex to the center of the tank and $Q_{\text{prompt}}$ is the sum of photoelectrons for PMTs with prompt hits.

The values of $\chi_a$ again provide distinction between electrons and neutrons. Relativistic electrons produce Čerenkov light whereas the heavier protons have velocities below the Čerenkov threshold. Thus electrons typically yield lower $\chi_a$ values than neutrons. This separation in values of $\chi_a$ for electrons and neutrons is due to a different physical effect than that which produces the separation in $\chi_r$. The two can be combined and serve to augment each other when used for particle identification.

5.3.5 Particle Identification

Besides $\chi_r$ and $\chi_a$, we use one more variable, $\chi_t$, for particle identification. $\chi_t$ is a measure of "late light" within the detector. We define a hit as late if the corrected PMT time $(t_i - r_i/v)$ is greater than the reconstructed event time, $t_0$, by 12 ns or more. $\chi_t$ is then defined as the ratio of number of PMTs with late hits to the total number of hit PMTs.
As mentioned earlier, due to its production mechanism, scintillation light tends to generate late PMT hits within the LSND detector. Heavier particles like a proton produce only scintillation light as compared to electrons which produce both scintillation and Čerenkov light. Thus protons tend to yield higher $\chi_t$ values than electrons. Also a neutron can knock out two or more protons resulting in a spread in the time distribution and, possibly, higher values for $\chi_t$. We use $\chi_t$ as a final input parameter for the purpose of particle identification.

$\chi_{tot}$ is defined as the product of $\chi_r$, $\chi_a$, and $\chi_t$.

$$\chi_{tot} = 30 \chi_r \chi_a \chi_t$$

This dissertation uses $\chi_{tot}$ to provide discrimination between the electrons and heavier particles like the neutrons and protons. To illustrate the use of $\chi_{tot}$ as a particle identification parameter we will first gather samples of electrons and neutrons.

As mentioned earlier, cosmic ray induced events generate the vast majority of interactions within the detector, far outnumbering the neutrino events. We have already discussed the Michel electron sample as being a pure and abundant source of electron events within the detector. The distribution of time, $dt$, between the muon and the subsequent electron for the Michel sample is shown in Fig. 5.1. An exponential decay, when plotted using a logarithmic scale along the vertical axis, should show a linear drop-off with increasing values of $dt$. However, some events in the Michel sample are not produced via the muon decay reaction. These are termed "accidentals" because two events, uncorrelated in time, mimic the muon-Michel pair. The
accidental events, by definition, yield a flat $dt$ distribution. When the observed $dt$ distribution was fit to an exponential plus a constant, the fit yielded a lifetime of 2.14 $\mu s$ for muon decay. This agreed well with the decay lifetime (2.15 $\mu s$) for a proper mixture of cosmic-ray $\mu^+$ and $\mu^-$ in mineral oil. Observe that there are no values of $dt$ smaller than 15.2 $\mu s$. This is because of the veto hold triggering requirement described in the previous chapter. Also note the small value for the flat background, signifying a high purity (>98%) of Michel electrons within the sample.
Interactions induced by cosmic-ray neutrons are another major source of events at LSND. Choosing events with few veto hits and ensuring that Michel events are avoided by searching for and eliminating events with prior activity, one can obtain what we will loosely term a "neutron sample".

Neutrons produce visible interactions within the detector by transferring energy to protons in inelastic collisions. The neutron subsequently thermalizes within the detector and may produce a 2.2 MeV gamma if it is captured by a free proton. The thermalization process results in a characteristic neutron capture lifetime of 186 $\mu$s for mineral oil. The correlation, in time, between a neutron event and its subsequent gamma for our neutron sample is shown in Fig. 5.2. We once again notice the accidental and the correlated components when we fit the time distribution, $dt$, to a constant plus an exponential. For any variable, we can obtain its distribution for a "pure" neutron sample by using a subtraction procedure described below. We obtain the distribution for the chosen variable using the entire sample and a distribution due to the accidental component by choosing only events with large $dt$. We then subtract the appropriately resized accidental distribution from the total distribution to obtain the final distribution for a pure neutron sample.

We can now use our Michel sample and neutron sample to illustrate the particle identification parameter, $\chi_{tot}$. Fig. 5.3 shows the $\chi_{tot}$ distribution for a pure electron sample (shaded) compared to that for a pure neutron sample. The $\chi_{tot}$ variable also provides good distinction between the electrons and the muons for energy regions of interest to this dissertation. This is because at DAR energies muons are not relativistic and, like the heavier protons, produce only scintillation light.
5.4 Energy Calibration

The sample of Michel electrons was used for energy calibration of the detector. The theoretical energy spectrum for Michel electrons is given by

$$\frac{dN}{dE} \propto E^2 (3 - \frac{2E}{E_{\text{end}}})$$

where $E$ is the energy in MeV and $E_{\text{end}} = 52.8$ MeV is the end-point energy of the Michel spectrum.

Assuming the detector energy resolution is proportional to $1/\sqrt{E}$ for an energy $E$, we can add this resolution effect to the theoretical spectrum. The resulting curve is then fit to the observed energy spectrum.
At LSND, events are detected by the light they produce in the detector. The light output is measured by summing the charge of photoelectrons at each hit PMT to obtain the total charge, $Q$. Thus $Q$ is a measure of the event energy and one has to obtain the conversion factor, $\Delta Q/\Delta E$, defined as the average number of photoelectrons generated for a loss of 1 MeV in electron energy within the detector. $\Delta Q/\Delta E$ and the detector energy resolution are treated as free parameters to be determined from the fit to the observed Michel data. A typical value of $\Delta Q/\Delta E$ is 35 and it varies from year to year due to changes in the gain calibration. The detector resolution at the Michel end-point energy is about 7-8\%.

Figure 5.3: The $\chi^2_{tot}$ distribution for electrons (shaded) and neutrons.
There is a slight dependence of $Q$, the total charge deposited, on certain variables. One such variable is $\text{dist}$, the shortest distance from the event vertex to a conceptual surface passing through all the PMT faces. This imaginary surface lies at the periphery of the detector, parallel to the tank walls. Thus $\text{dist}$ is a measure of the depth of an event within the detector. It is also used to define the fiducial volume within the tank. For example a $\text{dist} > 35$ cm requirement for an analysis states that an event will chosen if it lies at least 35 cm away from the phototube surface.

Let us now discuss the charge response of the detector as a function of the $\text{dist}$ value of an event. Imagine an electron event located at the center of the detector (large $\text{dist}$) for which we measure the charge deposited, $Q$. Now imagine moving this event towards the outer surface of the detector (lowering $\text{dist}$) and measuring the charge for these different event positions. We observe that $Q$ slightly but monotonically increases as we lower $\text{dist}$ until we reach a $\text{dist}$ of about 25 cm. From here on $Q$ decreases sharply, especially around $\text{dist} \sim 0$ cm, because the geometric acceptance of light drops as one approaches the outer edges of the detector.

Fortunately we have a large sample of Michel electrons distributed throughout the detector which we can use to correct for this variation of charge with $\text{dist}$. We divide the $\text{dist}$ variable into seven bins and for each bin obtain a fit to the Michel data and extract the $\Delta Q/\Delta E$ information. This information is then used to calculate the energy of an event, correcting for the $Q$ dependence on $\text{dist}$. 

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There exist four other variables which we correct for in the same fashion as above. The charge response is also dependent on the direction of the event and its reconstruction time. There are additional dependences on the $y$ and the $z$ positions of the event. All these corrections, combined, amount to changes of less than 10% from the uncorrected energy values. For the 1995 data, these corrections resulted in a 15% improvement in the detector energy resolution. Fig. 5.4 shows the energy distribution of the Michel electrons (shaded region) with the solid curve showing the fit to this distribution. The fit yields an energy resolution (denoted by P2) of 6.6% at the end-point energy of 52.8 MeV.

One can verify the linearity of the energy scale obtained from this calibration. At LSND we measure the cross-section of the reaction

$$\nu_e + ^{12}C \rightarrow e^- + ^{12}N_{g.s.},$$

where $^{12}N_{g.s.}$ is the ground state of the nitrogen nucleus. The electron from this reaction has an end-point energy of 35.4 MeV and the observed energy spectrum is consistent with this end-point.

The nitrogen ground state subsequently beta-decays via the reaction

$$^{12}N_{g.s.} \rightarrow ^{12}C + e^+ + \nu_e.$$ 

So for a ground state event, we require the detection of a positron in delayed coincidence with an electron. This positron has an end-point energy of 16 MeV, again consistent with our observed beta-decay spectrum.
Figure 5.4: A fit (solid line) to the observed Michel energy distribution (shaded), yielding detector resolution of 6.6% at 52.8 MeV.

5.5 Detector Simulation

A detailed Monte Carlo simulation, LSNDMC [46], was written using the CERN GEANT package to simulate events in the detector. The goal of the simulation was a complete description of events in the LSND detection apparatus.

This dissertation uses only simulation data obtained from the tank. We will briefly discuss portions of the simulation program which are relevant to our analysis. More information can be found elsewhere [47].
The GEANT geometry package was used to define the tank. The tank PMTs were positioned in the simulation to mirror their actual location within the tank. They were represented as having hemispherical photocathodes, although one had the option of switching to their real ellipsoidal shape. The PMT response to light was modelled, as was the electronics associated with each PMT channel.

Both Čerenkov and scintillation light were simulated in detail and each optical photon was tracked until it was absorbed or it arrived at a phototube surface.

The simulation program required a position and a momentum for each detector event one wished to simulate. One could use an internal generator which produced a sample of events distributed uniformly within the detector and uniformly in a preselected range of energy. If one desired an event sample occurring due to a particular process, one employed an external generator program. This program uses a theoretical model for the chosen reaction to produce a list of positions and momenta, in the required format, to be used as input for the detector simulation program.

Using the external generator, we obtained a sample of simulated Michel electrons. This sample could then be directly compared to the Michel data sample for quantities like the measured electron energy and the fraction of Čerenkov light to scintillation light generated in the tank. Fig. 5.5 shows that the simulated Michel energy distribution (dashed line) compares well with the observed distribution, shown in solid.
Figure 5.5: The Michel energy distribution for data (shaded) and simulation (dashed line).

The simulated sample of Michel electrons was also used to measure the detector position and angular resolutions. The actual positions and momenta of the simulated particles are input to the simulation. The reconstructed positions and directions are obtained using the event reconstruction algorithm. One can then compare the reconstructed values to the actual values for each event. Using these comparisons, we obtain a position resolution of 20 cm and an angular resolution of 12° for the sample of simulated Michel electrons.
The analysis presented in this dissertation selects a subset of events from the total data sample by imposing restrictions on some variables. For example, an event is considered for selection if its energy, $E$, lies within the range $18 < E < 50$ MeV. This restriction will be referred to as a "cut" in energy. The author used the detector simulation to obtain acceptance information due to the cut in energy, as described below.

Theoretical models within the external generator were first employed to generate streams of events for each of the various neutrino-electron elastic scattering and neutrino-nucleus processes. The generated streams were input to the detector simulation program and the output, which was designed to mirror real observed events, was written out in the same data format and subjected to the same event reconstruction procedure as the observed events. These simulated events were then subjected to the energy cut and the fraction of events which survived the cut was termed as acceptance of the cut.

A cut is also employed to select events for which the detected electron points along the direction of the incident neutrino. This angle cut, discussed in the next chapter, is designed to select most of the elastic scattering events while rejecting other neutrino induced events and cosmic-ray backgrounds. The acceptance of this angle cut is also obtained using the detector simulation program.
In this chapter we discuss the procedure for selecting neutrino-electron elastic scattering events while attempting to minimize the background from neutrino-nucleus processes and cosmic-ray interactions.

At LSND, the neutrino itself is not seen within the detector but we infer its presence by recording other particles produced as a result of neutrino interactions. For the neutrino-electron elastic scattering process

$$\nu + e^- \rightarrow \nu + e^-,$$

we observe the recoil electron which is produced at the point of interaction.

Our goal is to measure the cross-section for the elastic scattering process where, specifically, the neutrino is of the electron type. All other neutrino induced processes at LSND which result in production of electrons are a source of background that must be considered in the analysis.

6.1 Electron Neutrino-Electron Elastic Scattering

This reaction

$$\nu_e + e^- \rightarrow \nu_e + e^-,$$

as described in Chapter 1, proceeds via both charged current and neutral current channels. The analysis presented in this dissertation is designed to measure the cross-section of this reaction.
We detect the electron and can obtain its energy and direction of travel, as described in the previous chapter. Let us define $\Theta$ as the angle between the electron direction and the direction of the incident neutrino. Fig. 6.1 shows the energy distribution and the distribution of $\cos \Theta$ for a sample of simulated electrons obtained for the $\nu_e e^- \rightarrow \nu_e e^-$ elastic scattering process.

![Energy and CosTheta Distributions](image)

Figure 6.1: The energy and $\cos \Theta$ distributions for electrons produced via the $\nu_e e^- \rightarrow \nu_e e^-$ reaction.

Each plot of simulated data shown in this thesis was generated using the following procedure. First, a theoretical model for the process being studied and the neutrino energy spectrum were employed to generate events. The detector response to each event was then simulated using the detector Monte Carlo simulation program and the output was processed in the same fashion as real data. Thus these plots will reflect all detector resolution effects seen in real data.

As explained in Chapter 1, Section 1.3.3, the kinematics of the $\nu_e e^- \rightarrow \nu_e e^-$ reaction dictates that the $\cos \Theta$ distribution is sharply forward peaked.
This feature will allow us to separate elastic scattering events from neutrino-nucleus events.

6.2 Neutrino-Electron Elastic Scattering for Muon-type Neutrinos

The DAR chain produces $\nu_\mu$, $\bar{\nu}_\mu$ and $\nu_e$, each with the same relative intensity as described in Chapter 2. The energy spectra of these neutrinos is shown in Fig. 6.2.

![Figure 6.2: The energy distributions of DAR neutrinos.](image)

Neutrino-electron elastic scattering can proceed via the two reactions

$$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$$

and

$$\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$$

in addition to the $\nu_e e^- \rightarrow \nu_e e^-$ process discussed in the previous section.
The two reactions involving neutrinos of the muon type ($\nu_\mu$ and $\bar{\nu}_\mu$) can proceed only through the neutral current interaction. As a result their cross-sections are small compared to the $\nu_e e^- \rightarrow \nu_e e^-$ reaction. We expect only about 22% of all neutrino-electron scattering events to occur due to neutrinos of the muon type.

The energy and $\cos \Theta$ distributions, for simulated electrons produced via the $\nu_\mu e^- \rightarrow \nu_\mu e^-$ reaction, are shown in Fig. 6.3. The corresponding plots for the $\bar{\nu}_\mu e^- \rightarrow \bar{\nu}_\mu e^-$ process are shown in Fig. 6.4.

![Figure 6.3: The electron energy and $\cos \Theta$ distributions for the $\nu_\mu e^- \rightarrow \nu_\mu e^-$ process.](image)

At LSND, we cannot distinguish $\nu_\mu$ and $\bar{\nu}_\mu$ interactions with electrons from $\nu_e$ interactions on electrons. Thus we will obtain a sample of all elastic scattering events and subtract the expected contribution due to neutrinos of the muon type.

We also have a source of $\nu_\mu$ from DIF neutrinos. However, this DIF contribution to the elastic scattering is very small as we will see later.
6.3 Neutrino-Nucleus Interactions

Chemically, mineral oil is composed of a linear chain hydrocarbon molecule \((C_nH_{2n+2})\) where \(n\) varies from 22 to 26. Isotopically, the carbon content is 98.9\% \(^{12}\text{C}\) and 1.1\% \(^{13}\text{C}\).

At DAR energies, \(\nu_\mu\) and \(\bar{\nu}_\mu\) interact with carbon and hydrogen nuclei only through elastic scattering and do not produce any electrons. Also \(\nu_e\) reactions with protons do not yield electrons. The charged current (CC) reactions of \(\nu_e\) on carbon do produce electrons and are of interest to us.

6.3.1 CC Interactions of \(\nu_e\) on \(^{12}\text{C}\)

The \(\nu_e^{12}\text{C} \rightarrow e^- X\) reaction can be divided into two components depending on the product \(X\). If \(X\) is the ground state of nitrogen \((^{12}\text{N}_{g.s.})\), we classify the event as a "nitrogen ground state" event.

\[
\nu_e + ^{12}\text{C} \rightarrow e^- + ^{12}\text{N}_{g.s.}\]
We can identify a ground state event because, following the detection of the $e^-$. the $^{12}N_{g.s.}$ beta-decays via the reaction

$$^{12}N_{g.s.} \rightarrow ^{12}C + \nu_e + e^+$$

and we detect the positron in delayed coincidence with the electron.

Due to the $e^-e^+$ coincidence we can cleanly extract a sample of ground state events. Also the theoretical cross-section for this process is well known. Hence the measurement of this cross-section provides a good check for the experiment.

Complimentary to the ground state reaction, we have transitions to excited states of $^{12}N$. They proceed via the reaction

$$\nu_e + ^{12}C \rightarrow e^- + ^{12}N^*$$

where $^{12}N^*$ is an excited state and excludes $^{12}N_{g.s.}$. The excited states decay by prompt proton emission and thus do not feed down to the $^{12}N_{g.s.}$ or contribute to the delayed coincidence rate.

The LSND collaboration has published cross-sections [48] for both these reactions and the results will be discussed below.

6.3.1.1 The Nitrogen Ground State Reaction

Plots for the electron energy and the $\cos \Theta$ distribution for a sample of simulated electrons generated for the ground state reaction are shown in Fig. 6.5.

Notice that the cut-off in electron energy is significantly below the endpoint energy of the $\nu_e$ spectrum due to the difference in energy between the $^{12}N_{g.s.}$ and the $^{12}C$ nuclear states. Also notice the asymmetry in the $\cos \Theta$
Figure 6.5: The electron energy and cos $\Theta$ distributions for the $^{12}\text{C}(\nu_e, e^-)^{12}\text{N}$ reaction.

distribution which indicates that there is more scattering in the backward direction than in the forward direction.

The LSU group was primarily responsible for the analysis of $\nu_e$-Carbon data at LSND. For the nitrogen ground state, a cross-section of $(9.1 \pm 0.4 \pm 0.9) \times 10^{-42}\text{cm}^2$ was measured [48] which compared well with the various theoretical predictions. Below we show some plots from this analysis to indicate how the measured quantities compared with their expected values.

The measured energy distribution of the detected electron is shown in Fig. 6.6 with the solid curve showing the expected energy distribution. Fig. 6.7 shows the energy distribution of the positron from the $^{12}\text{N}_{2,3}$ beta-decay, observed in coincidence with the electron. The good agreement between the observed and the expected distributions shows that the energy calibration works well even at low energies.
Figure 6.6: The energy distribution for electrons produced in the ground state reaction.

Figure 6.7: The energy distribution for the beta-decay positron.
The lifetime of the nitrogen ground state decay is 15.2 ms. Fig. 6.8 shows the observed time distribution between the electron and the positron. The expected time distribution, shown by the solid line, agrees well with the observed time distribution. The dotted line shows the accidental component.

![Figure 6.8: The time distribution between the electron and the subsequent positron in the ground state reaction.](image)

6.3.1.2 The Reaction to the Excited States

For the $^{12}$C($\nu_e, e^-)^{12}$N process, we detect only the electron. Thus events from this reaction and a fraction of events from the ground state reaction where we do not detect the positron combine to produce a neutrino-induced background for the neutrino-electron elastic scattering events.

The energy and $\cos \Theta$ distributions for a sample of simulated electrons generated for this reaction are shown in Fig. 6.9. We observe that the $\cos \Theta$ distribution is more backward peaked than for the ground state reaction.
The LSND collaboration has measured a cross-section of \((0.7 \pm 0.6 \pm 0.6) \times 10^{-42}\text{cm}^2\) [48] for the \(^{12}\text{C}(\nu_e, e^-)^{12}\text{N}^*\) reaction which should be compared to the cross-section from a recent CRPA calculation [49] of \(6.3 \times 10^{-42}\text{cm}^2\).

Fig. 6.10 shows a plot of the measured electron energy distribution compared to the expected (solid curve) distribution for this reaction.

6.3.2 CC interactions of \(\nu_e\) on \(^{13}\text{C}\)

The charged current interaction

\[
\nu_e + ^{13}\text{C} \rightarrow e^- + X.
\]

where \(X\) is any final state of \(^{13}\text{N}\), results in the production of electrons. The contribution to neutrino induced background from this reaction is small because \(^{13}\text{C}\) comprises only about 1% of the carbon in LSND. However, the cross-section of \(\nu_e\) on \(^{13}\text{C}\) is larger than that on \(^{12}\text{C}\). Thus this background to the \(\nu_e e^-\) elastic scattering process is not insignificant.
Figure 6.10: The energy distribution for electrons produced in the $^{12}\text{C}(\nu_e, e^-)^{12}\text{C}^*$ reaction.

6.4 Cosmic-ray Background

Cosmic-ray interactions can produce electron or electron-like events within the detector. Certain standard selection criteria, to be discussed in the next section, were devised to reduce this cosmic-ray (CR) background. Despite these efforts, due to the high rate of cosmic-ray interactions we still have a sizable CR background.

There are two major sources of CR background. Michel electrons, produced in the decay of cosmic-ray muons, contribute a large fraction of events to the CR background.

A second source of CR background is attributed to neutrons produced by cosmic-ray muons. Those cosmic-ray muons which enter the tank, barring
any inefficiency, are detected and tagged in the veto. But those that miss the tank may produce neutrons in the outer shielding material. These neutrons may enter the tank undetected by the veto. A small fraction of these neutrons are misidentified as electrons. However, due to the large number of cosmic-ray neutrons entering the detector we have a substantial source of cosmic-ray electron-like events due to misidentified neutrons.

Having discussed the CR background, we should point out that this background can be measured and then subtracted to yield only the beam-induced events. At LSND, the detector is operational irrespective of whether the proton beam is present (beam is on) or absent (beam is off). The beam cycle, as explained in Chapter 2, operates so that the beam is on approximately 6% of the time. During the beam-off period we attribute all detected events to cosmic-ray interactions. We now describe the beam-on minus beam-off subtraction procedure used to eliminate the CR background.
The duty ratio is defined as the ratio of time the beam is present to the time it is absent. The sample of Michel electrons is gathered independent of the beam status. This is a large and clean sample, ideal for the determination of the duty ratio. Here, the duty ratio is the ratio of the number of beam-on to beam-off Michel electrons. The duty ratio was calculated individually for each year of data collection, as shown in Table 6.1. Various other samples were also used to determine the duty ratio. For example, a very large sample of all primary events was used. For this sample, beam-induced neutrino events accounted for only about 1 in $10^5$ triggers and were a negligible perturbation to the duty ratio calculation. All samples yielded, within error, the same duty ratio.

For any sample of selected events, we use the duty ratio to resize its beam-off component to obtain a beam-on cosmic-ray contribution. We then subtract this contribution from the beam-on component of the sample. Quantitatively,

$$N_{\text{excess}} = N_{\text{on}} - \text{duty ratio} \times N_{\text{off}}$$

where $N_{\text{excess}}$ is the number of beam-excess events produced due to neutrino
interactions. $N^{on}$ ($N^{off}$) is the number of beam-on (beam-off) events for the given sample of events.

This procedure should remove all cosmic-ray related events from the beam-on data sample regardless of the size of the CR background. However, the larger the CR background, the larger the statistical error associated with this subtraction. It is desirable to reduce this error by decreasing the size of the CR background, especially for cases like the present analysis which have large statistical errors.

Mathematically,

$$\sigma_{excess} = \sigma_{on} + \text{negligible term},$$

where $\sigma_{excess}$ ($\sigma_{on}$) is the error for the beam-excess (beam-on) sample. Thus, the relative error is given by

$$\frac{\sigma_{excess}}{N_{excess}} \approx \sqrt{\frac{N^{on}}{N_{excess}}}.$$

Writing $N^{on}$ as a sum of $N^{excess}$ plus the cosmic-ray subtraction term, we have.

$$\frac{\sigma_{excess}}{N_{excess}} \approx \sqrt{\frac{N^{excess} + \text{duty ratio} \times N^{off}}{N_{excess}}}$$

and observing that $N^{excess}$, barring any statistical fluctuation, is a constant for the given data sample, we can reduce the statistical error only by reducing the size of the CR background.

In the next section we will discuss event selection criteria which are designed to lower this background.
6.5 The Selection Criteria

The event selection procedure involves choosing a subset of events which are of interest to the analysis. This is achieved using a set of selection criteria. Each criterion, termed a cut, generally involves a variable in the analysis, whose range we limit via the cut. For example, the range in energy for the present analysis is limited to $18 < E < 50$ MeV.

For events belonging to a particular process, the acceptance of a cut is defined as the fraction of events which survive the cut. For example, our detector simulations indicate only 34% of the event sample for the $\nu_ee^- \rightarrow \nu_ee^-$ process, present before any energy cut was applied, survive the cut in energy yielding an acceptance of 0.34. Since a sample of real data events for the process being analysed is unavailable, we calculate the acceptance of a cut using a readily available sample which mirrors the behaviour of the real data sample for that particular cut.

Our goal was to design cuts that have a large acceptance for the $\nu e^-$ elastic scattering process while reducing the background due to other neutrino induced processes and cosmic-ray interactions. In this section we will define all the cuts and discuss their functionality. We will also discuss the process of obtaining the acceptance of each cut.

It should be mentioned that if two or more cuts are correlated, their acceptance values will depend on the order in which the cuts are made. Below we will list the cuts in the order in which we apply them. Starting from the top when we apply a cut which is next on the list, we imply that all the cuts prior to it have already been applied. We obtain and report the acceptance value of each cut by proceeding in this same fashion.
6.5.1 The Fiducial Volume Cut

The variable dist was defined in the previous chapter as the shortest distance from the event vertex to the phototube surface. The cut dist > 35 cm requires all events to be reconstructed with their vertices at least 35 cm away from the phototube surface. This excludes the outermost region of the detector and helps discriminate against cosmic-ray particles which enter the tank. This exclusion also alleviates the problem of calculating the various detector responses which vary more rapidly near the phototube surface.

The acceptance of the dist cut was determined from an analysis of stopped muon events for which both the muon and the subsequent electron were detected. The decay electrons were required to satisfy a minimum energy cut. No fiducial cut was imposed on this sample and other than the energy requirement essentially all muons which stopped in the tank and decayed were included in the analysis sample. For comparison, a sample of stopped muon events was generated using the detector simulation program.

For the decay electron, the observed and the generated dist distributions were compared. The observed distribution was found to be shifted outward relative to the generated distribution. This meant that there was a slight reconstruction bias which tended, on average, to push the reconstructed vertex towards the outer edge of the detector. Various independent analyses [50, 51] were used in determining an acceptance value of 0.85 ± 0.05 for the dist cut.

6.5.2 The $y > -120 \text{ cm}$ Cut

We employ a $y > -120 \text{ cm}$ cut which, like the dist cut, depends on the position of the event within the detector - in particular its position along
the vertical (Y) axis. The $y > -120$ cm cut removes a strip, $(-160 < y < -120$ cm)$^1$, from the bottom of the tank. This cut was imposed because there is a large CR background at the bottom of the detector due to the absence of a veto counter below the detector. Fig. 6.12 shows a plot of the $y$ distribution for cosmic-ray events. The shaded region shows events that are excluded by the $y > -120$ cm cut. The sample of events plotted in Fig. 6.12 is obtained by choosing only the beam-off component with all the cuts mentioned in this section in force except for the $y > -120$ cm cut.

![Graph showing $y$ distribution of cosmic-ray events.]

Figure 6.12: The $y$ distribution of cosmic-ray events.

The acceptances of each cut, including the $y > -120$ cm cut, for the $\nu_e e^- \rightarrow \nu_e e^-$ process are listed later in Table 6.3.

$^1$The dist $> 35$ cm cut implies $y > -160$ cm at the bottom of the tank.
6.5.3 The Energy Cut

We observe from the simulated energy distribution of Fig. 6.1 that the energy distribution drops off with increasing energy. Hence the lower the energy cut we set, the higher will be its acceptance.

Unfortunately, if we go below 18 MeV we start picking up large CR backgrounds as seen in Fig. 6.13. Again, we plot only the beam-off component of a sample selected using the entire set of cuts except for the energy cut. Events excluded by the $E > 18$ MeV cut are shown by the shaded region. For our analysis we select a $18 < E < 50$ MeV cut.

Figure 6.13: The energy distribution for cosmic-ray events.

One source of CR background below 18 MeV arises from cosmic-ray $\mu^-$ which stop in the detector and are captured on carbon. This reaction pro-
duces boron which subsequently beta-decays via the reaction

\[ ^{12}B \rightarrow ^{12}C + \bar{\nu}_e + e^- . \]

The beta-decay electron has an end-point energy of 13.4 MeV. However, owing to detector resolution effects and the high rate of production of this background we observe its high energy tail in Fig. 6.13. The \( E > 18 \) MeV cut eliminates most of the background from this source.

This 18 MeV energy cut also eliminates most of the neutrino-induced background due to 15.1 MeV gammas. These are produced in the neutral current neutrino-carbon reaction. \( ^{12}C(\nu, \nu')^{12}C^{*} \). The \( ^{12}C^{*} \) nucleus de-excites via the emission of a 15.1 MeV gamma. The electromagnetic interactions of the gammas within the detector can mimic electron events. However the 18 MeV energy cut eliminates most of this background.

The acceptance of the energy cut is obtained from a sample of simulated events generated for the desired neutrino reaction and processed to resemble real data using the detector Monte Carlo simulation program.

6.5.4 The PID Cut

In the previous chapter we saw that the \( \chi_{tot} \) variable could be used for particle identification. The \( \chi_{tot} < 0.85 \) cut used in the present analysis serves to reduce the background due to cosmic-ray neutrons.

To calculate the \( \chi_{tot} \) acceptance for the \( \nu_e e^- \rightarrow \nu_e e^- \) process, we have to account for the fact that the \( \chi_{tot} \) variable has an energy dependence. We use a sample of Michel electrons to determine this acceptance. However, the Michel energy spectrum differs from the energy spectrum due to the \( \nu_e e^- \) elastic scattering process. We correct for this by weighing each event of the Michel
sample according to its energy to obtain a final energy distribution of the weighted Michel sample which resembles that for the $\nu_e e^-$ elastic scattering process. This weighted sample then yields the proper acceptance.

6.5.5 The In-time Veto Cut

This cut eliminates events which produce activity in the veto system in addition to the interaction within the tank. Thus this cut mainly eliminates cosmic-ray muons.

For events to survive the cut, we require

$$veto\ hits + crack\ hits < 4$$

and

$$no\ activity\ in\ the\ bottom-edge\ counters,$$

where, for each event, the variable $veto\ hits$ ($crack\ hits$) denotes the sum of hit veto (crack counter) PMTs. This composite cut will be termed the "in-time veto" cut because we use hits in the veto system that occur during the time-span (500 ns) of the event.

The Michel electron sample provides a good source for determining the acceptance of this cut since for this sample, like any sample of neutrino-induced events, we do not expect activity in the veto system which is correlated to the primary event. Thus we can calculate the acceptance from the fraction of Michel events which survive the in-time veto cut.

6.5.6 The Cut for Prior Activity

As we mentioned earlier, Michel electrons are a major contributor to the CR background. They are produced when cosmic-ray muons stop and decay
within the tank with an expected decay lifetime of 2.15 μs. To reduce this background, we search for any activity prior to a primary event which may be attributed to a muon.

In Chapter 4 we discussed a feature of the trigger software, the 15.2 μs veto-hold which prevents the broadcast of a primary if there is an activity in the veto within a 15.2 μs period prior to the primary. This veto-hold requirement reduced the triggers from Michel electrons by a factor of $10^3$.\(^2\) We extend this triggering requirement by selecting only events which have no activity either in the veto or the tank for at least 20 μs prior to the primary event. This requirement reduces the background from cosmic-ray Michel electrons by a factor of $10^4$.

In addition, for a period of 20-35 μs prior to the primary event we have a modified requirement which was designed to selectively identify cosmic-ray muons without causing a large reduction in electron acceptance. Cosmic-ray muons generally travel a fair distance into the detector and thus generate a lot of charge. For any activity in the 20-35 μs interval prior to the event, we term it as a cosmic-ray muon and reject the primary event from our data sample if

$$Q > 3000$$

or

$$tank \ hits > 100 \ and \ veto \ hits + crack \ hits \geq 4,$$

where $Q$, as before, is the total charge in photoelectrons generated at the detector PMTs and $tank \ hits$ is the corresponding sum of hit detector PMTs.

\(^2\)Every 5 μs interval leads to, approximately, a factor of 10 reduction.
The $Q$ value of 3000 is approximately equivalent to a muon energy deposit of 100 MeV within the tank.

This composite cut will be referred to as the $\Delta t_{\text{past}} > 20,35 \mu s$ cut and its acceptance is calculated using a sample of laser events. The laser events can be used as random strobes and, as is the case for neutrino-induced events, we do not expect any correlated activities prior to the laser events. Hence we can calculate the acceptance for all neutrino-induced events by determining the fraction of laser events which survive the $\Delta t_{\text{past}}$ cut.

### 6.5.7 The Cut for Future Triggers

This cut has two components. The first is designed to eliminate muons which are misidentified as electrons. If these subsequently decay to produce Michel electrons, we can search for triggers recorded in the future. Thus, for any primary event, if within 8.8 $\mu$s into its future we detect a trigger with tank hits $> 75$, we identify it as a Michel electron and reject the original event.

The second component is designed to eliminate nitrogen ground state events. For these events, we first detect an electron via the process

$$\nu_e + ^{12}\text{C} \rightarrow e^- + ^{12}{\text{N}}_{g.s.}.$$  

Then $^{12}_{}{\text{N}}_{g.s.}$ beta-decays via the reaction

$$^{12}_{}{\text{N}}_{g.s.} \rightarrow ^{12}\text{C} + \nu_e + e^+$$

with a lifetime of 15.9 ms. The beta-decay positron has an end-point energy of 16.8 MeV. We identify a subsequent trigger as the positron if it satisfies the following criteria:
tank hits > 75 (100 for 1994 data).

\[ E < 18 \text{MeV}. \]

\[ \text{dist} > 0. \]

in-time veto cut.

\[ 52 \mu s < \Delta t < 45 \text{ms. and } \]

\[ \Delta r < 1 \text{m.} \]

where \( \Delta t \) (\( \Delta r \)) is the time interval (distance) between the \( e^-e^+ \) pair.

The acceptance of this composite cut, termed the \( \Delta t_{\text{future}} \) cut, is once again determined from laser events. Only a small fraction of laser events satisfy the muon or beta identification cuts due to accidental coincidences. We calculate the acceptance for elimination of the muon separately from that for elimination of the beta. We then combine the two to obtain the acceptance of the \( \Delta t_{\text{future}} \) cut, as seen in Table 6.2.

<table>
<thead>
<tr>
<th>Cut</th>
<th>Acceptance value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elimination of muon</td>
<td>0.998 ± 0.001</td>
</tr>
<tr>
<td>Elimination of beta</td>
<td>0.985 ± 0.001</td>
</tr>
<tr>
<td>( \Delta t_{\text{future}} )</td>
<td>0.983 ± 0.001</td>
</tr>
</tbody>
</table>

6.5.8 The \( \cos \Theta \) Cut

We notice that the \( \cos \Theta \) distribution for all three \( \nu e^- \) elastic scattering processes is sharply forward peaked. To select these processes and discriminate against the backward peaked neutrino-nucleus interactions we use a \( \cos \Theta > 0.9 \) cut.
Table 6.3: The Acceptances for the $\nu e^- \rightarrow \nu e^-$ Process.

<table>
<thead>
<tr>
<th>Cut</th>
<th>Acceptance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$dist &gt; 35cm$</td>
<td>0.85 ± 0.05</td>
</tr>
<tr>
<td>$y &gt; -120cm$</td>
<td>0.915 ± 0.015</td>
</tr>
<tr>
<td>$18 &lt; E &lt; 50 MeV$</td>
<td>0.34 ± 0.01</td>
</tr>
<tr>
<td>$\chi_{tot} &lt; 0.85$</td>
<td>0.894 ± 0.010</td>
</tr>
<tr>
<td>In-time veto</td>
<td>0.981 ± 0.005</td>
</tr>
<tr>
<td>$\Delta t_{past} &gt; 20.35\mu s$</td>
<td>0.682 ± 0.005</td>
</tr>
<tr>
<td>$\Delta t_{future}$</td>
<td>0.983 ± 0.001</td>
</tr>
<tr>
<td>$\cos \Theta &gt; 0.9$</td>
<td>0.82 ± 0.01</td>
</tr>
<tr>
<td>DAQ Dead Time</td>
<td>0.97 ± 0.01</td>
</tr>
<tr>
<td>Total Acceptance</td>
<td>0.124 ± 0.010</td>
</tr>
</tbody>
</table>

This cut has a large acceptance for the $\nu e^-$ elastic scattering events but is conservative in the sense that it lies below the sharply falling edge of the $\cos \Theta$ distribution for these elastic scattering events. This choice minimizes the uncertainty in the calculated acceptance of the $\cos \Theta$ cut. The acceptance of this cut is obtained from a sample of simulated Monte Carlo events for the required process.

6.6 The Acceptance Values

The acceptance value of each cut along with its error for the $\nu e^- \rightarrow \nu e^-$ process is listed in Table 6.3. For a small fraction of the time, the detector was unable to collect data mainly due to overwriting of data at a channel FIFO. The DAQ dead time variable, listed as one of the cuts, records the acceptance value due to this effect.

Earlier, we have discussed the various neutrino induced processes which are a background to the $\nu e^- \rightarrow \nu e^-$ process. The acceptances of all the cuts...
Table 6.4: The Total Acceptances for the Different Neutrino Processes.

<table>
<thead>
<tr>
<th>Process</th>
<th>Total Acceptance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e e^- \rightarrow \nu_e e^-$</td>
<td>$0.124 \pm 0.010$</td>
</tr>
<tr>
<td>$\nu_e e^- \rightarrow \nu_e e^-$</td>
<td>$0.105 \pm 0.008$</td>
</tr>
<tr>
<td>$\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-$</td>
<td>$0.116 \pm 0.009$</td>
</tr>
<tr>
<td>$^{12}C(\nu_e, e^-)^{12}N_{g.s.}$</td>
<td>$0.0073 \pm 0.0006$</td>
</tr>
<tr>
<td>$^{12}C(\nu_e, e^-)^{12}N^-$</td>
<td>$0.0065 \pm 0.0004$</td>
</tr>
<tr>
<td>$^{13}C(\nu_e, e^-)X$</td>
<td>$0.0227 \pm 0.0021$</td>
</tr>
</tbody>
</table>

for each neutrino-induced background were recalculated if needed. We list only the total acceptance, due to the combination of all cuts, for each of these processes and compare them to the total acceptance for the $\nu_e e^- \rightarrow \nu_e e^-$ process in Table 6.4. It should be noted that for the $^{12}C(\nu_e, e^-)^{12}N_{g.s.}$ process, the $\Delta t_{future}$ cut excludes events with an identified beta. The acceptance for that process is thus calculated for cases where we do not detect a beta.

6.7 Summary

In this chapter we have discussed the various neutrino-induced and cosmic-ray backgrounds to the $\nu_e e^-$ elastic scattering process. We then described the cuts we used in obtaining a preliminary sample of elastic scattering events. However, we have not completed our discussion of the selection procedure. In the next chapter we will discuss two more cuts that were designed specifically to further reduce the cosmic-ray background. The explanation of how both these cuts were constructed and then applied is more involved than the cuts described above and we will devote the next chapter to this discussion.
CHAPTER 7

REDUCTION OF COSMIC-RAY BACKGROUND

In this chapter we describe two additional cuts which are specifically designed to further reduce the CR background. The first cut is designed to reduce a background whose source will be traced to cosmic-ray muons. It is based on a ratio of likelihoods which utilizes the veto information from look-back events. The description of this likelihood analysis as well as its results will be discussed in Section 7.2.

The second cut is aimed at reducing the background arising from neutrons produced via cosmic-ray interactions. A neutron interacts within the detector, producing a primary event. It subsequently thermalizes and may be captured via the reaction

\[ n + p \rightarrow d + \gamma, \]

yielding a 2.2 MeV gamma. Thus the detection of a gamma in conjunction with a primary event signals that the primary event may be neutron induced. In Section 7.3 we will construct a likelihood analysis, using information from gammas, to identify and reject the neutron induced events.

7.1 Motivation for Reduction of CR Background

In the previous chapter we chose primary events of interest to the \( \nu_e e^- \) elastic scattering process by applying all the cuts discussed in Chapter 6, Section 6.5. We term the sample of events thus selected as our “preliminary sample”.

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For this sample let us plot the energy distribution for beam-on events, shown by the solid curve of Fig. 7.1. Also shown is the cosmic-ray subtraction (dashed curve), obtained by normalizing beam-off data to the period the beam was on. The energy distribution of beam-excess events, produced via neutrino interactions, is then obtained by subtracting the dashed curve from the solid curve.

As mentioned in Chapter 6, Section 6.4 the lower the cosmic-ray subtraction, the lower the statistical error for the measurement. Thus in this chapter we seek to reduce the CR background of our preliminary sample by constructing two likelihood analyses described below.
7.2 Likelihood Analysis of Look-back Events

As discussed in Chapter 4, Section 4.2 we use threshold values for detector and veto hits to make triggering decisions. For any event to be recorded as an activity, it must meet or exceed a threshold requirement of 18 hits in the detector and/or 6 hits in the veto. In the previous chapter we have discussed cuts to eliminate primary events with prior activities because we attribute such a pair of events to a cosmic-ray muon and its subsequent decay electron. Look-back events were designed to check a 6 $\mu$s interval prior to a primary event and ensure that the primary event was not produced as a result of a prior event which itself escaped detection by producing fewer hits than the activity threshold.

Look-back events were introduced for data collected from 1995 onwards. All PMT hits that occur in the two intervals 0-3 and 3-6 $\mu$s prior to primary events are recorded, separately, as two look-back events. This is done for both the detector and the veto PMTs. For this dissertation we will use only the look-back information from the veto to identify cosmic-ray muons which escape detection in the veto and subsequently produce the primary event.

Due to hardware constraints not all primary events could be written out with look-back information. For the 1995 run, only those primaries with 300 or more PMT hits in the detector and no activity within the past 35 $\mu$s were chosen to have look-back events. From 1996 onwards the timing requirement was lowered to no activity within the past 20 $\mu$s. Also for this look-back analysis we will choose only primary events that are contained within our preliminary sample.
The majority of cosmic-ray muons are tagged in the veto. A few muons, however, pass through with fewer than 6 hits. If these muons enter the detector and travel more than a few centimeters (\( \text{dist} > 35 \text{ cm} \) for our sample), they will produce more than 18 detector hits and get tagged as activities prior to the primary electron event.

When we examined the look-back veto information, we noticed events with 4 or 5 veto hits, clustered in space and time. We measured the time interval between these events and the subsequent primary events. The time interval plot showed a characteristic muon lifetime, superimposed on a flat background as seen in Fig. 7.2. Thus cosmic-ray muons which escape tagging in the veto and do not enter the detector, appear to produce subsequent electron-like events within the detector fiducial volume.

We hypothesize that such an electron-like event results from the following process. The muon stops, possibly in the walls of the tank, and decays to give a Michel electron. The electron then radiates a hard photon via Bremsstrahlung which enters the tank to produce the observed electron-like event. This process can explain electron-like events occurring well inside the detector because the mean \( \gamma \) absorption length for events in our energy range is about 60 cm.

**7.2.1 Objectives of the Look-back Analysis**

Our aim for this analysis is to reduce the CR background but at the same time minimize the loss in electron acceptance so as not to reduce the size of our data sample.

In the next subsection we will outline a procedure for scanning each 3 \( \mu s \) look-back interval in order to locate activity in the veto shield. We define
the veto activity to be correlated if it produces the subsequent primary event within the detector. A time interval plot between look-back veto activities and subsequent primary events in the detector is shown in Fig. 7.2. The correlated component exhibits a $2.15 \mu s$ exponential muon lifetime distribution. This is superimposed on a flat background which occurs because of those veto activities that are not correlated with the subsequent primary events. We shall henceforth term these events as "accidentals". Note that the fitted fraction of these accidentals is about 25% of the total number of events.

The correlated component represents a source of CR background and we seek to eliminate this component from our elastic scattering sample. If we
eliminate the accidentals along with the correlated component, we suffer a substantial loss in electron acceptance. Thus we have to, somehow, differentiate between the correlated and the accidental component so as to mostly target the correlated component for elimination. To accomplish this, we will introduce a procedure to determine the ratio, \( L \), of likelihood that an event is correlated to the likelihood that it is accidental. Fig. 7.3 shows the time interval plot, now for events with \( L > 1 \). The accidental component is reduced to a fraction of a percent and is now not visible on the plot.

\[\text{Figure 7.3: The time distribution between the look-back activity and the primary event for the correlated (} L > 1 \text{) component.}\]
7.2.2 Extraction of Information from Look-back Events

The author of this dissertation was responsible for developing the following procedure for extracting information from look-back events for use in all data analyses performed at LSND. The data from both the detector and the veto is subject to this procedure but we will only discuss the veto information in this dissertation.

The 3 µs look-back event was divided into smaller time intervals, within which we counted the number of veto hits. To determine the optimal length of this time window we looked at a sample of stopping cosmic-ray muons. Only those muons with 6 or 7 veto hits were chosen so as to be similar to our look-back sample with fewer than 6 veto hits. We observed that most of these 6 or 7 hits lay within a 100 ns window. Hence we chose to divide the 3 µs interval into 100 ns windows, with any two consecutive windows overlapping by 50 ns so as not to skip any cluster of veto hits. The 100 ns window with the largest number of veto hits was chosen for a more detailed analysis. The number of veto hits \((nhits)\) within this 100 ns window and the cumulative charge \((Q)\) generated by these hits are recorded. The time interval \((\Delta t)\) between this window and the subsequent primary event is noted. Also the mean \(x\), \(y\) and \(z\) positions for these hits are calculated, along with their spatial rms values. A measure of the spatial spread, \(\sigma_R\), of these events was obtained

\[
\sigma_R = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2}.
\]

In order to obtain events which are clustered in space, we chose \(\sigma_R < 2\) m. For the sample of stopped cosmic-ray muons described above, we observed only a small loss in acceptance for the \(\sigma_R < 2\) m cut.
7.2.3 Construction of the Likelihood Ratio

We will employ four variables in this likelihood analysis that show some discrimination between the correlated and the uncorrelated (accidental) components. Instead of applying individual cuts to each of these variables, we will construct approximate likelihood functions for the correlated \( \mathcal{L}_{\text{cor}} \) and uncorrelated \( \mathcal{L}_{\text{uncor}} \) components. Then the ratio, \( L \), defined as

\[
L = \frac{\mathcal{L}_{\text{cor}}}{\mathcal{L}_{\text{uncor}}}
\]

is a measure of how much the event in question and its corresponding look-back activity resemble a correlated pair of events, in contrast to an accidental pairing of events. Thus, for each event, we input the values of four variables and receive as output a single number, \( L \), which we can use to identify and eliminate the correlated component.

For each variable, we must construct a probability density function (pdf), separately, for the correlated and the accidental components. We have already discussed the first variable, \( \Delta t \). We expect a characteristic muon lifetime distribution for the correlated pdf of \( \Delta t \). The accidental pdf is, by definition, flat.

Any look-back activity prior to laser events is clearly accidental. We will use the laser sample to extract the accidental pdfs for each of the remaining three variables. Let us examine the variable \( n\text{hits} \). Fig. 7.4 shows the pdf of \( n\text{hits} \) for the correlated component (solid line) and the accidental component (dashed line). The correlated pdf is obtained indirectly. This requires a bigger sample of events which we obtain by eliminating the \( \cos \Theta \) cut. The \( \Delta t \) plot is used to determine the number of accidental events within this.
sample. Then the accidental pdf is subtracted from the pdf of this entire sample, in proportion to the calculated accidental events, and renormalized to give the pdf for the correlated sample.

![Graph of nhits](image)

Figure 7.4: The pdf for $nhits$, the correlated (accidental) component is shown by the solid (dashed) line.

The correlated pdf shows a peak at 5 veto hits, indicating that we are picking up as correlated events, muons which just miss the trigger threshold of six veto hits. We also see some events with 6 or more veto hits. This is because, for the likelihood analysis, we use all the veto hits in the 100 ns window whereas the trigger accepts only those hits which satisfy the electronic fine-time requirement. Also notice in Fig. 7.4 the clear separation between the correlated and the accidental components which indicates the the variable $nhits$ is suitable for the likelihood analysis.
Figure 7.5: The pdf for veto charge per hit tube, the correlated (accidental) component is shown by the solid (dashed) line.

The third variable used is veto charge per hit tube ($Q/n\text{hits}$). Fig. 7.5 shows that the veto charge per hit tube for the accidental component (dashed line) is much smaller than that for the correlated component (solid line). This is because part of the accidental component is comprised of a collection of random hits due to noise in the veto shield which do not produce as many photoelectrons as a real charged particle passing through the veto. Events due to neutron interactions or radioactivity would also have, on average, a smaller value of veto charge per hit tube. The final variable used is the approximate track length, in the tank, of the photon which we presume enters the detector and ultimately produces an electron-like event. We use the position of the cosmic-ray muon in the veto, obtained from the look-
back information, and the position of the primary event within the tank to calculate track length, as shown in Fig. 7.6. The pdf of track length for the correlated component (solid line) and for the accidental component (dashed line) are shown in Fig. 7.7. The spread in the accidental pdf distribution reflects the fact that for a primary event, the corresponding accidental lookback activity in the veto is randomly located.

The pdfs of all four variables were combined into a likelihood function for the correlated and the uncorrelated components. As mentioned earlier, if a primary satisfies the conditions to have a look-back, there are two intervals (0-3 and 3-6$\mu$s) for which we read out look-back data. Information from each interval is processed independently and we calculate a likelihood ratio for both these intervals. The larger of the two likelihood ratios, which we will henceforth refer to as $L$, is the ratio that is finally associated to the primary event. The Log($L$) distribution for a sample of accidental (correlated) events is shown by the solid (dashed) line in Fig. 7.8. Observe the clear separation we achieve between the two samples for this distribution.

We studied the correlated events ($L > 1$) to understand their origin and verify our earlier hypothesis that they are associated with radiative photons. In Fig. 7.9, we plot the detector hit distribution, tank hits, for primary events from the preliminary sample, requiring $L > 1$. The solid curve shows the 300 PMT hit cut which the primary event must satisfy in order to have a lookback. This plot also shows the rapid energy drop-off one would expect for Bremsstrahlung photons. These photons arise from Michel electrons whose hit distribution is shown by the dashed line for comparison.
Figure 7.6: The calculation of track length for the gamma.

Figure 7.7: The pdf for track length. The correlated (accidental) component is shown by the solid (dashed) line.
Figure 7.8: The log likelihood ratio (Log(L)), shown for the correlated component (dashed line) and the accidental component (solid line).

We can see more clearly that for the correlated component the primary event is a result of a radiative photon by plotting its $dist$ distribution. For display purposes, the $dist$ distribution is weighted in such a way that a uniform distribution of events within the detector volume would show a flat $dist$ distribution. Fig. 7.10 shows that the $dist$ distribution for events with $L > 1$ decreases exponentially with a decay length of 55 cm, consistent with the expected distribution for absorption of gammas in mineral oil.

Thus the look-back analysis has identified a source of CR background attributable to cosmic-ray muons which pass undetected by producing fewer than six veto hits and subsequently produce electron-like events within the
Figure 7.9: The tank hit distribution for the correlated \((L > 1)\) component (solid line). The distribution for Michel electrons (dashed line) is shown for comparison.

Figure 7.10: The weighted \(\text{dist}\) distribution for the correlated \((L > 1)\) component. A fit to this distribution (solid line) exhibits an exponential decay length of 55 cm.
tank. To reduce this background, we eliminate all events with $L > 1.5$\textsuperscript{1} for the present analysis.

The beam-off component of our preliminary event sample has a large proportion of events at the front end (low $z$) of the detector, as seen in Fig. 7.11. Fig. 7.12 shows a scatter plot of events eliminated by the likelihood analysis, where the $Y$ ($Z$) axis of the detector is plotted along the vertical (horizontal) axis of the figure and the location of each event is indicated by a diamond. We observe that the eliminated events are also grouped at low $z$.

We chose the $L > 1.5$ cut after studying the effects of varying this cut. For the 1995 data, Table 7.1 shows the fraction of beam-off events eliminated as a result of different cuts in $L$. Also shown are the corresponding losses in electron acceptance due to the $L$ cut. For example, the $L > 1.5$ cut results in the elimination of 39\% of the beam-off events if we consider only those events which have a look-back. But, as we have mentioned earlier, not all primary events have look-backs. Thus for the total beam-off sample we eliminate 22\% of the beam-off data. This cut results in only a 1.3\% loss in electron acceptance. This loss was calculated using a laser sample because for laser events we do not expect any correlated activities in the veto, similar to real neutrino-electron elastic scattering events.

Observing the second column in Table 7.1, we note that the likelihood analysis attributes a significant fraction of beam-off events to the cosmic-ray muon source we are discussing. In addition, there exists some inefficiency

\textsuperscript{1}We assign $L = 0$ to all primary events that have no look-back activity.
Figure 7.11: The $z$ distribution of beam-off events in our preliminary sample.

Figure 7.12: A $y$ v/s $z$ scatter plot of events eliminated by the look-back analysis.
Table 7.1: Effects of Cuts in Likelihood Ratio $L$.

<table>
<thead>
<tr>
<th>Likelihood Ratio Cut</th>
<th>% Eliminated (with look-back)</th>
<th>% Eliminated (all primaries)</th>
<th>% Loss in Electron Acceptance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L &gt; 0.5$</td>
<td>44</td>
<td>25</td>
<td>2.7</td>
</tr>
<tr>
<td>$L &gt; 1.0$</td>
<td>40</td>
<td>23</td>
<td>1.7</td>
</tr>
<tr>
<td>$L &gt; 1.5$</td>
<td>39</td>
<td>22</td>
<td>1.3</td>
</tr>
<tr>
<td>$L &gt; 3.0$</td>
<td>34</td>
<td>19</td>
<td>0.8</td>
</tr>
<tr>
<td>$L &gt; 5.0$</td>
<td>30</td>
<td>17</td>
<td>0.5</td>
</tr>
</tbody>
</table>

within the likelihood analysis in identifying these muons. Thus we estimate that for our preliminary sample (before any $L$ cut), at least half of the beam-off events are due to this source. In the next section we will deal with neutrons produced via cosmic-ray interactions. We estimate that they contribute about 30% of the beam-off background. Thus we understand the source of at least 80% of the cosmic-ray background\(^2\) for our preliminary sample.

It should be noted that we did not have look-back events for the 1994 data. Accounting for this, we recalculate, for the $L > 1.5$ cut, the fraction of the total beam-off events eliminated and the electron acceptance using the entire data sample. We obtain an electron acceptance of $0.991 \pm 0.002$ and a 14% reduction in beam-off background.

7.3 Likelihood Analysis to Eliminate Neutrons

We have mentioned in Chapter 6, Section 6.4 that we have a source of CR background attributable to neutrons. These neutrons interact within the detector and produce primary events, a small fraction of which satisfy the

\(^2\)The beam-off background is totally attributed to cosmic-ray interactions.
$\chi_{\text{tot}} < 0.85$ cut to yield electron-like events that are contained within our data sample. Our goal, in this section, is to reduce the background due to such events.

A gamma window is a 1 ms interval subsequent to each primary event, for which we lower the trigger threshold to 21 detector PMT hits. This window was designed to record gamma events that are produced by neutrons via the following process. A neutron thermalizes within the detector and may undergo the capture reaction

$$n + p \rightarrow d + \gamma,$$

yielding a 2.2 MeV gamma. The neutron has a mean capture time of 186 $\mu$s in mineral oil, independent of its initial energy.

Thus the detection of a correlated gamma within the gamma window signals the presence of a neutron. We will develop a likelihood analysis which is designed to separate neutron induced events from events without a neutron. This analysis builds on a likelihood analysis developed for the DAR oscillation search [40].

### 7.3.1 Likelihood Analysis for the DAR Oscillation Search

At LSND, we conduct a DAR neutrino oscillation search in the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ channel. We detect positrons produced via the reaction

$$\bar{\nu}_e + p \rightarrow e^+ + n.$$

The recoil neutron has a much lower energy (0-5.2 MeV) than the positron and does not generally contribute to the primary event. But it thermalizes and may undergo the capture reaction
\[ n + p \rightarrow d + \gamma. \]

yielding a 2.2 MeV gamma. Thus the detection of a correlated gamma in delayed coincidence with the positron is a signal for the DAR oscillation process.

For those primary events which have one or more gammas recorded within their gamma window, we must examine each gamma and determine the likelihood that it is produced as a result of the primary event (correlated) or it is due to some accidental occurrence within the detector (uncorrelated). We use three variables for this purpose: (a) the time distribution of the gamma from the primary event, (b) the number of hit PMTs for the gamma, and (c) the distance of the gamma from the primary event. The distribution of these variables, for both the correlated component (solid line) and the accidental component (dashed line), is shown in Fig. 7.13. The accidental distributions are obtained using a sample of laser events since we do not expect any correlated gammas for this sample. The correlated distributions are extracted from a sample of cosmic-ray neutrons, as explained in Ref. [40].

The exponential time distribution of the gamma from the primary event for the correlated component shows the correct neutron capture lifetime while the corresponding accidental component is flat as expected. We attribute the accidental gammas to radioactivity within the detector and observe that, on average, they produce fewer PMT hits than the correlated gammas. Also notice that the correlated gammas are, on average, located closer to the primary event than the accidental gammas as one would expect.
Figure 7.13: Distributions for correlated (solid) and uncorrelated (dashed) gammas for the variables: (a) the time between the primary and the $\gamma$, (b) the number of PMT hits for the $\gamma$, and, (c) the distance between the primary and the $\gamma$. 

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Using these three variables, approximate likelihood functions were created for the correlated ($\mathcal{L}_{\text{corr}}$) and the uncorrelated ($\mathcal{L}_{\text{uncorr}}$) components. As before, a likelihood ratio, $R$, was defined as

$$R = \frac{\mathcal{L}_{\text{corr}}}{\mathcal{L}_{\text{uncorr}}}.$$ 

If there was no gamma within 1 ms and 2.5 m from a primary event, we assigned a value of $R = 0$ to the primary event. If for a primary event we detected two or more gammas, we calculated the $R$ value for each of the gammas and assigned the largest $R$ value to the primary event.

The $R$ analysis was used to efficiently separate events with correlated gammas from events with accidental gammas. The $R > 30$ cut for our DAR oscillation analysis [40] identified events with correlated gammas while eliminating a large fraction (99.4%) of events with accidental gammas.

### 7.3.2 Addition to the $R$ Analysis

We are interested in separating out and excluding neutron induced events from our sample of neutrino-electron elastic scattering events. To accomplish this we will adopt the oscillation search $R$ analysis. However, in our case the $R$ analysis serves to identify and eliminate those primary events which produce correlated gammas while reducing the elimination of events with accidental gammas. This reduction is essential for lowering the loss in electron acceptance for this cut.

In addition to the gamma information used in the $R$ analysis, we will also utilize information from the primary event for our analysis. We seek to eliminate primary events that are neutron induced and, as we have seen in Chapter 5. Section 5.3.5 the particle identification parameter, $x_{\text{tot}}$, provides
discrimination between electrons and neutrons. Thus we add $\chi_{tot}$ to the three variables used in the R analysis.

The $\chi_{tot}$ probability density function (pdf) for the neutron (non-neutron) component is shown by the solid (dashed) line in Fig. 7.14. For our data sample, the non-neutron component is dominated by electrons from the neutrino-electron elastic scattering process. We obtain the $\chi_{tot}$ pdf for this component using a sample of weighted Michel electrons. The weights in energy were adjusted so that the energy spectrum of this sample matched the corresponding spectrum for elastic scattering events. The $\chi_{tot}$ pdf for the neutron component was obtained using a cosmic-ray neutron sample. We used the time interval plot between the primary and the gamma to calculate the number of non-neutron events within this sample. Next we determined the $\chi_{tot}$ distribution for the neutron sample and subtracted the non-neutron $\chi_{tot}$ pdf in proportion to the number of non-neutron events to obtain a distribution for pure neutrons.

We define a new likelihood ratio,

$$N = \mathcal{L}_{neut} / \mathcal{L}_{non-neut},$$

where $\mathcal{L}_{neut}$ ($\mathcal{L}_{non-neut}$) is the approximate likelihood function for the neutron induced (non-neutron) component.

The $N$ value for primaries with multiple gammas was calculated in the same fashion as their $R$ values. Also a primary event was assigned $N = 0$ if there were no gammas within 1 ms and 2.5 m from it. For primary events with one or more identified gammas, the solid (dashed) line in Fig. 7.15 shows the $\log(N)$ distribution for the neutron (non-neutron) component.
Figure 7.14: The $\chi_{\text{tot}}$ pdf, the neutron (non-neutron) component is shown by the solid (dashed) line.

After studying the effect of various $N$ cuts, we chose to eliminate events with $N > 1.5$ in the present analysis. The preliminary sample of events obtained by applying all the cuts described in the previous chapter and prior to any cut described in this chapter was used as the starting sample for this study. Limiting ourselves to a smaller, more convenient subset of 1995 data for now, we list, in Table 7.2, the fraction of beam-off events which are eliminated by each cut in $N$. We also list the loss in electron acceptance for any beam-induced neutrino process due to each cut. These values of losses in electron acceptance were calculated using a laser sample.
Figure 7.15: The $\log(N)$ distribution, shown in solid (dashed) for the neutron (non-neutron) component.

Using data from all years, we eliminate 15% of the beam-off events with the $N > 1.5$ cut. The percent loss in electron acceptance for this entire data sample is calculated to be $2.0 \pm 0.2$.

7.4 Combination of the Likelihood Cuts

Applying both the $L > 1.5$ and $N > 1.5$ cuts, we obtain a 28% reduction in the CR background of our preliminary sample. The reduction due to each cut applied separately and then in combination is listed in Table 7.3.

The electron acceptance for the $\nu_e e^- \rightarrow \nu_e e^-$ process due to the $L > 1.5$ cut and the $N > 1.5$ cut is shown in Table 7.4. The final electron acceptance for this process, obtained by combining all cuts in the previous chapter with
Table 7.2: Effects of Cuts in Likelihood Ratio $N$.

<table>
<thead>
<tr>
<th>Likelihood Ratio Cut</th>
<th>% Eliminated (beam-off events)</th>
<th>% Loss in Electron Acceptance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N &gt; 0.5$</td>
<td>21</td>
<td>3.9</td>
</tr>
<tr>
<td>$N &gt; 1.0$</td>
<td>19</td>
<td>2.5</td>
</tr>
<tr>
<td>$N &gt; 1.5$</td>
<td>17</td>
<td>1.8</td>
</tr>
<tr>
<td>$N &gt; 3.0$</td>
<td>14</td>
<td>1.0</td>
</tr>
<tr>
<td>$N &gt; 7.0$</td>
<td>12</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Table 7.3: Combining the $L$ and $N$ Cuts.

<table>
<thead>
<tr>
<th>Likelihood Ratio Cut</th>
<th>% Eliminated (beam-off events)</th>
<th>% Loss in Electron Acceptance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L &gt; 1.5$</td>
<td>14</td>
<td>0.9</td>
</tr>
<tr>
<td>$N &gt; 1.5$</td>
<td>15</td>
<td>2.0</td>
</tr>
<tr>
<td>Combined</td>
<td>28</td>
<td>2.9</td>
</tr>
</tbody>
</table>
Table 7.4: Final Acceptance for the $\nu_e e^- \rightarrow \nu_e e^-$ Process.

<table>
<thead>
<tr>
<th>Cut</th>
<th>Acceptance</th>
</tr>
</thead>
<tbody>
<tr>
<td>All cuts listed in Chap. 6</td>
<td>0.124 ± 0.010</td>
</tr>
<tr>
<td>Eliminate events with $L &gt; 1.5$</td>
<td>0.991 ± 0.002</td>
</tr>
<tr>
<td>Eliminate events with $\mathcal{V} &gt; 1.5$</td>
<td>0.980 ± 0.002</td>
</tr>
<tr>
<td>Final Acceptance</td>
<td>0.120 ± 0.010</td>
</tr>
</tbody>
</table>

Table 7.5: Final Acceptances for $\nu$ Induced Backgrounds.

<table>
<thead>
<tr>
<th>Process</th>
<th>Final Acceptance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu e^- \rightarrow \nu_\mu e^-$</td>
<td>0.102 ± 0.008</td>
</tr>
<tr>
<td>$\bar{\nu}<em>\mu e^- \rightarrow \bar{\nu}</em>\mu e^-$</td>
<td>0.113 ± 0.009</td>
</tr>
<tr>
<td>$^{12}\text{C}(\nu_e, e^-)^{12}\text{N}_{g.s.}$</td>
<td>0.0071 ± 0.0006</td>
</tr>
<tr>
<td>$^{12}\text{C}(\nu_e, e^-)^{12}\text{V}^*$</td>
<td>0.0063 ± 0.0004</td>
</tr>
<tr>
<td>$^{13}\text{C}(\nu_e, e^-).X$</td>
<td>0.0220 ± 0.0020</td>
</tr>
</tbody>
</table>

The two likelihood cuts discussed in this chapter, is calculated as 0.120±0.010.

The corresponding final acceptances for various neutrino induced processes which are backgrounds to the $\nu_e e^- \rightarrow \nu_e e^-$ process are listed in Table 7.5.
CHAPTER 8

RESULTS

In this chapter we determine the $\nu_e e^- \rightarrow \nu_e e^-$ cross section using our sample of beam-excess events, obtained by applying all the cuts discussed in the previous two chapters and then subtracting the beam-off cosmic-ray background from the beam-on events. This beam-excess data contains $\nu_e e^-$ elastic scattering events plus background due to other neutrino induced events.

First, we present our calculation of the neutrino induced background. Next, we compare various distributions of beam-excess data with expectations. Then we obtain the neutrino flux and number of target electrons. Finally, we present the results of our analysis: we calculate the cross section for the $\nu_e e^-$ elastic scattering reaction and determine the interference term, $I$. This term arises because the reaction can proceed through both charged current and neutral current interactions.

8.1 Neutrino Induced Background

In this section, we list all sources of neutrino induced background for our analysis and calculate the expected number of events from each source. We have already discussed most of the sources of neutrino induced background in Chapter 6. Below we provide additional descriptions for three sources of this background.
8.1.1 The 15.1 MeV Gamma Source

The 15.1 MeV gammas are produced due to neutral current interactions of neutrinos on carbon.

\[ \nu + ^{12}C \rightarrow \nu' + ^{12}C^{*}. \]

The \(^{12}C^{*}\) nucleus de-excites via the emission of a 15.1 MeV gamma.

Electromagnetic interactions of the gammas within the detector can produce electron-like events. We have an energy cut of \(E > 18\) MeV but due to finite detector resolution effects we expect a small background of \(8 \pm 3\) electron-like events due to this source.

8.1.2 Source due to DIF \(\nu_{\mu}\)

As discussed in Chapter 2, we have a flux of decay-in-flight (DIF) \(\nu_{\mu}\) which is an order of magnitude smaller than the decay-at-rest (DAR) flux. We expect a small contribution of \(4 \pm 2\) events from DIF \(\nu_{\mu}\) which undergo the elastic scattering reaction.

\[ \nu_{\mu} + e^{-} \rightarrow \nu_{\mu} + e^{-}. \]

8.1.3 Source due to DAR Oscillations

A DAR \(\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}\) oscillation would produce \(\bar{\nu}_{e}\) that interact in our detector via the reaction.

\[ \bar{\nu}_{e} + p \rightarrow n + e^{+}. \]

The positrons would then be a source of background for our \(\nu_{e}e^{-}\) elastic scattering sample.

At LSND we perform a DAR oscillation search [40] and obtain an excess of events consistent with neutrino oscillations. If we attribute this excess to
neutrino oscillations, we determine an oscillation probability of $(0.3 \pm 0.1)\%$. Using this probability, we calculate a background of 16 events due to this source. However, the $N > 1.5$ cut eliminates $47\%$ of these events because DAR oscillation events produce correlated gammas. Accounting for this, we expect a background of $8 \pm 3$ events due to the DAR oscillation source.

Even if we did not attribute this background to neutrino oscillations, we would still have a background due to an unknown, non-conventional source of $\bar{\nu}_e$. Fortunately this background is small and if we were to ignore it and calculate the cross section for the $\nu_e e^-$ elastic scattering process, we would obtain a value only $6\%$ higher than our final cross section.

8.1.4 Calculation of Background

The numerical contributions, in terms of number of events, for all source of the neutrino induced background were calculated using the measured cross sections listed in Table 8.1. We list these sources of background together with their respective contributions in Table 8.2. Along with the number of events due to each source, we state a corresponding systematic error. This error was generally obtained from the total error in the cross section measurement, as listed in Table 8.1. However, for some cases where the cross sections were also measured at LSND, we accounted for correlations in errors so as not to count them twice. For example, we omit here the error in the neutrino flux for the $\nu_e^{12C}$ interactions because we will include this same error later for our measurement.

We calculate a background of 95 events due to all neutrino induced sources other than the $\nu_e e^-$ elastic scattering process. For this background we cal-
Table 8.1: Measured Cross Sections for the Background Processes.

<table>
<thead>
<tr>
<th>Process</th>
<th>Experiment</th>
<th>Cross section (cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu e^- \rightarrow \nu_\mu e^-$</td>
<td>CHARM [36]</td>
<td>$(1.9 \pm 0.28) \times E_\nu$(MeV) $\times 10^{-45}$</td>
</tr>
<tr>
<td>$\bar{\nu}<em>\mu e^- \rightarrow \bar{\nu}</em>\mu e^-$</td>
<td>US-JAPAN [37]</td>
<td>$(1.25 \pm 0.19) \times E_\nu$(MeV) $\times 10^{-45}$</td>
</tr>
<tr>
<td>$^{12}C(\nu_e, e^-)^{12}N_{g.s.}$</td>
<td>LSND [48]</td>
<td>$(9.1 \pm 0.4 \pm 0.9) \times 10^{-42}$</td>
</tr>
<tr>
<td>$^{12}C(\nu_e, e^-)^{12}N_*$</td>
<td>LSND [48]</td>
<td>$(5.7 \pm 0.6 \pm 0.6) \times 10^{-42}$</td>
</tr>
<tr>
<td>$^{13}C(\nu_e, e^-).X$</td>
<td>KARMEN [52]</td>
<td>$(0.5 \pm 0.3 \pm 0.1) \times 10^{-40}$</td>
</tr>
<tr>
<td>15.1 MeV gamma</td>
<td>KARMEN [53]</td>
<td>$(10.9 \pm 0.7 \pm 0.8) \times 10^{-42}$</td>
</tr>
<tr>
<td>DAR oscillations</td>
<td>LSND [40]</td>
<td>$(0.3 \pm 0.1)%$ osc. probability</td>
</tr>
</tbody>
</table>

Table 8.2: Background from $\nu$ Induced Events.

<table>
<thead>
<tr>
<th>Process</th>
<th>Contribution to background</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu e^- \rightarrow \nu_\mu e^-$</td>
<td>$17 \pm 2$</td>
</tr>
<tr>
<td>$\bar{\nu}<em>\mu e^- \rightarrow \bar{\nu}</em>\mu e^-$</td>
<td>$16 \pm 2$</td>
</tr>
<tr>
<td>$^{12}C(\nu_e, e^-)^{12}N_{g.s.}$</td>
<td>$24 \pm 2$</td>
</tr>
<tr>
<td>$^{12}C(\nu_e, e^-)^{12}N_*$</td>
<td>$13 \pm 1$</td>
</tr>
<tr>
<td>$^{13}C(\nu_e, e^-).X$</td>
<td>$5 \pm 3$</td>
</tr>
<tr>
<td>15.1 MeV gamma</td>
<td>$8 \pm 3$</td>
</tr>
<tr>
<td>DIF $\nu_\mu e^- \rightarrow \nu_\mu e^-$</td>
<td>$4 \pm 2$</td>
</tr>
<tr>
<td>DAR oscillations</td>
<td>$8 \pm 3$</td>
</tr>
<tr>
<td>Total</td>
<td>$95 \pm 10$(stat) $\pm 7$(syst)</td>
</tr>
</tbody>
</table>
Table 8.3: Events due to the $\nu_e^- \rightarrow \nu_e^-$ Process.

<table>
<thead>
<tr>
<th>Source</th>
<th>Number of Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam-on</td>
<td>372 ± 19</td>
</tr>
<tr>
<td>Cosmic-ray Subtraction</td>
<td>144 ± 4</td>
</tr>
<tr>
<td>Beam-excess</td>
<td>228 ± 19</td>
</tr>
<tr>
<td>$\nu$ Induced Background</td>
<td>95 ± 10</td>
</tr>
<tr>
<td>$\nu_e^- \rightarrow \nu_e^-$</td>
<td>133 ± 22</td>
</tr>
</tbody>
</table>

culate a statistical error of $\sqrt{95} \approx 10$ events and a systematic error of 7 events, obtained by summing in quadrature the systematic errors due to each source.

8.2 Beam-excess Sample

We apply all the cuts listed in Chapters 6 and 7 to obtain our sample of $\nu_e^-\nu_e^-$ elastic scattering events. We then perform the beam-on minus beam-off subtraction as described in Chapter 6, Section 6.4 to obtain the beam-excess sample. This subtraction procedure, barring any statistical fluctuations, removes all cosmic-ray induced events from our final sample of beam-excess events. For our analysis, we have a beam-excess sample of 228 events with an uncertainty of 19 events due to statistical error. We attribute these events to either $\nu_e^-\nu_e^-$ elastic scattering events or the $\nu$ induced background. In Table 8.3, we calculate the number of events due to the $\nu_e^-\nu_e^-$ elastic scattering process (133 ± 22) by subtracting the calculated $\nu$ induced background from the sample of beam-excess events.

Each error listed in Table 8.3 is solely due to the statistical uncertainty associated with its value. We obtain a final statistical error of 16% for the $\nu_e^-\nu_e^-$ elastic scattering events.
Let us plot the variable \(\cos \Theta\) for the sample of beam-excess events. Recall that \(\Theta\) is the angle between the electron direction and the direction of the incident neutrinos and that we require \(\cos \Theta > 0.9\) for our final sample. If we remove the \(\cos \Theta > 0.9\) cut from our selection criteria and then plot the \(\cos \Theta\) distribution for the beam-excess events of this sample (Fig. 8.1), we notice a clear accumulation of elastic scattering events in the last \((0.9 < \cos \Theta < 1)\) bin. For comparison, we also plot the expected \(\cos \Theta\) distribution, shown by the shaded region.

![Figure 8.1: The \(\cos \Theta\) distribution for beam-excess events, obtained when we eliminate the \(\cos \Theta > 0.9\) cut.](image)

We now reapply the \(\cos \Theta > 0.9\) cut and concentrate on the \(0.9 < \cos \Theta < 1\) region. The \(\cos \Theta\) distribution for the beam-excess events is shown in Fig. 9.1. The expected \(\cos \Theta\) distribution is also shown by the shaded re-
region. This distribution includes the $\nu_e e^-$ elastic scattering, calculated using the standard model of electroweak interactions, and the contribution from the neutrino induced background. The theoretical $\cos \theta$ distribution from each individual source is calculated and input into the detector Monte Carlo simulation program. The output of this program is summed for each source, in proportion to its contribution, to get the final expected $\cos \theta$ distribution. This expected distribution now mirrors that from real data and should be directly compared to the distribution of beam-excess events. We obtain good agreement between the observed and the expected distributions.

Figure 8.2: The $\cos \theta$ distribution for beam-excess events. The expected distribution is shown by the shaded region.
Fig. 8.3 shows the energy distribution for the beam-excess events. The shaded plot again shows the expected energy distribution for comparison. It is obtained as before but here we do not include the contribution from the DAR oscillation source. This is because the energy distribution due to this source depends on an oscillation parameter which is not yet known. Notice that the energy distribution of beam-excess data compares well with the expected distribution.

Figure 8.3: The energy distribution for beam-excess events. The expected distribution is shown by the shaded region.

Next, we show that the distribution of the beam-excess events within the detector agrees well with expectations. Fig. 8.4 shows the $x$, $y$ and $z$ distributions and Fig. 8.5 shows the $dist$ distribution for the sample of beam-
excess events. For these plots as well as Fig. 8.6, the expected distributions, shown as shaded regions, are calculated for the $\nu_e e^- \rightarrow \nu_e e^-$ process and normalized to the total number of beam-excess events.

![Graphs of x, y, and z distributions for beam-excess events.](image)

Figure 8.4: The $x$, $y$ and $z$ distributions for beam-excess events. The expected distributions are also shown as shaded.

Finally, a plot of the particle identification parameter, $\chi_{tot}$, is shown in Fig. 8.6. As before, the beam-excess data is shown using solid error bars. Two data points, normally excluded from our analysis by the $\chi_{tot} < 0.85$ cut, are also shown for comparison using dashed error bars. For this plot, we notice a fair agreement between the observed and the expected distributions.
Figure 8.5: The $dist$ distribution for beam-excess events.

Figure 8.6: The $\chi_{tot}$ distribution for beam-excess events.
8.3 Flux Calculations

For the 1994 and 1995 target set-up, a detailed beam Monte Carlo simulation program was used to calculate the neutrino flux at the LSND detector as described in Chapter 2, Section 2.4. However, after 1995 the A1 and A2 targets were removed and the main A6 target was replaced by a new tungsten target for the remainder of the data. One has to modify the beam simulation program by replacing the old target information with the geometry and constituent material information of the new target in order to obtain the correct neutrino flux for the 1996 and 1997 data. Unfortunately, this process had not been completed by the time this dissertation was prepared. The author had to obtain the flux for the 1996 and 1997 data using the number of nitrogen ground-state events observed in the different years of data collection.

For nitrogen ground-state events, we first detect an electron due to the reaction.

$$\nu_e + ^{12}C \rightarrow ^{12}N_{g.s.} + e^-.$$  

Subsequently, we detect a positron when $^{12}N_{g.s.}$ beta-decays via the reaction.

$$^{12}N_{g.s.} \rightarrow ^{12}C + \nu_e + e^+.$$  

The $e^-e^+$ coincidence requirement allows us to obtain a clean sample of ground-state events and the relatively large cross section of this reaction allows us to determine the flux with adequate statistical precision.

The author performed an independent analysis to obtain beam-excess ground-state events for each year of data collection. The results of this analysis are displayed in Table 8.4. The third column of this table lists the
Table 8.4: Nitrogen Ground-state Events.

<table>
<thead>
<tr>
<th>Year</th>
<th>Beam-excess Events</th>
<th>Events after Acceptance Corrections</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994</td>
<td>223</td>
<td>870</td>
</tr>
<tr>
<td>1995</td>
<td>285</td>
<td>943</td>
</tr>
<tr>
<td>1996</td>
<td>85</td>
<td>332</td>
</tr>
<tr>
<td>1997</td>
<td>197</td>
<td>715</td>
</tr>
</tbody>
</table>

Table 8.5: Flux Calculation.

<table>
<thead>
<tr>
<th>Years</th>
<th>Flux (νe/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994+1995</td>
<td>(6.47 ± 0.45) x 10^{13}</td>
</tr>
<tr>
<td>1996+1997</td>
<td>(3.74 ± 0.38) x 10^{13}</td>
</tr>
<tr>
<td>All years</td>
<td>(10.21 ± 0.77) x 10^{13}</td>
</tr>
</tbody>
</table>

calculated number of ground state events obtained after we correct for the detector acceptance. For example, for the 1994 data we have 223 beam-excess events and a total acceptance of 0.256 due to all the cuts used in this analysis. We obtain 870 (= 223/0.256) events after accounting for the loss due to acceptance for the 1994 data.

The flux for 1996 and 1997 data is proportional to the number of ground-state events obtained for that period:

\[(1996+1997 \text{ Flux}) = \left( \frac{332 + 715}{870 + 943} \right) (1994+1995 \text{ Flux}),\]

where we use the calculated flux for 1994 and 1995, obtained from the beam simulation program. The total flux for our data sample is summarized in Table 8.5.
As discussed in Chapter 2, Section 2.4 we assign a systematic error of 7% to all flux calculations obtained using the beam-simulation program. This 7% error is common to fluxes of all years. In addition, for the 1996 + 1997 flux we have a 7.4% error due to statistical fluctuations in the numbers of ground-state events for the different years. Thus we have a total error of 10.2% assigned to that portion of the flux. Finally, we obtain a total flux of \((10.2 \pm 0.8) \times 10^{13}\text{cm}^{-2}\) reflecting a total systematic error of 7.5%.

### 8.4 Target Calculation

The LSND detector is filled with mineral oil which serves as a target for neutrino interactions. Chemically, mineral oil is composed of linear chain hydrocarbon molecules \((C_nH_{2n+2})\) where \(n\) varies from 22 to 26. We measured a ratio of \(H/C = 2.05\) [47]. The number of impurity particles like nitrogen and oxygen were negligible: \(N/C \sim 3 \times 10^{-6}\) and \(O/C \sim 1.5 \times 10^{-6}\).

The mineral oil was kept at a constant temperature of \(\sim 15^\circ\) by a heat transfer unit. Its density was measured to be 0.85 g/cm\(^2\). Table 8.6 shows the composition of target particles within the detector and the number of particles contained within the fiducial volume \((dist > 35\text{ cm})\) for each of these targets. For our present analysis of \(\nu_e e^-\) elastic scattering, the electrons serve as the targets particles.

### 8.5 Calculation of the Cross Section

We calculate the cross section for the \(\nu_e e^- \rightarrow \nu_e e^-\) reaction using the number of events (133) obtained for this process, the final acceptance (0.120) calculated for this process, the flux \((10.2 \times 10^{13}\text{cm}^{-2})\) and the number of target electrons \((29.7 \times 10^{30})\).
Table 8.6: Target Composition.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Number within Fiducial Volume / 10^{30}</th>
</tr>
</thead>
<tbody>
<tr>
<td>^{12}\text{C}</td>
<td>(3.65 \pm 0.04)</td>
</tr>
<tr>
<td>^{13}\text{C}</td>
<td>(0.041 \pm 0.001)</td>
</tr>
<tr>
<td>H</td>
<td>(7.56 \pm 0.08)</td>
</tr>
<tr>
<td>e^-</td>
<td>(29.7 \pm 0.3)</td>
</tr>
</tbody>
</table>

Table 8.7: Sources of Systematic Error.

<table>
<thead>
<tr>
<th>Source of Systematic Error</th>
<th>Contribution towards uncertainty in cross section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptance Calculation</td>
<td>7.9%</td>
</tr>
<tr>
<td>Flux Calculation</td>
<td>7.5%</td>
</tr>
<tr>
<td>Subtraction of ( \nu ) Induced Background</td>
<td>4.9%</td>
</tr>
<tr>
<td>Target Calculation</td>
<td>1.0%</td>
</tr>
<tr>
<td>Total Systematic Error</td>
<td>12%</td>
</tr>
</tbody>
</table>

\[
\sigma_{\nu e^-} = \left( \frac{133}{0.120} \right) \left( \frac{1}{10.2 \times 10^{13}} \right) \left( \frac{1}{29.7 \times 10^{30}} \right) \text{cm}^2
\]

\[
= 3.67 \times 10^{-43}\text{cm}^2
\]

We have already mentioned that we calculate a 16% uncertainty in the cross section measurement due to statistical errors. Let us now discuss the systematic errors for this measurement.

In Table 8.7 we list the dominant sources of systematic error in the cross section measurement along with their contributions. We express each error as a percentage of the measured cross section. Adding up the errors from individual sources in quadrature we obtain a final 12% uncertainty in the cross section measurement due to all systematic effects.
Writing the cross section so as to explicitly indicate its linear dependence on the neutrino energy and using the average energy of the $\nu_e$ beam at LSND (31.7 MeV), we obtain

$$\sigma_{\nu_e e^-} = 3.67 \times \left( \frac{E_{\nu_e} \text{(MeV)}}{31.7 \text{ MeV}} \right) \times 10^{-43} \text{cm}^2.$$

Including all statistical and systematic errors, we obtain a final cross section of

$$\sigma_{\nu_e e^-} = [11.6 \pm 1.9 \text{(stat.)} \pm 1.4 \text{(syst.)}] \times E_{\nu_e} \text{(MeV)} \times 10^{-45} \text{cm}^2$$

for the process $\nu_e e^- \rightarrow \nu_e e^-$. We can compare our cross section to the cross section

$$\sigma^{E225}_{\nu_e e^-} = [9.9 \pm 1.5 \text{(stat.)} \pm 1.0 \text{(syst.)}] \times E_{\nu_e} \text{(MeV)} \times 10^{-45} \text{cm}^2$$

measured by experiment E225 [39] for the same process. Experiment E225 was also conducted at the LAMPF facility of Los Alamos National Laboratory and utilized a DAR $\nu_e$ beam of similar origin as LSND.

We can also compare our cross section to the theoretical value of

$$\sigma^{SM}_{\nu_e e^-} = 9.5 \times E_{\nu_e} \text{(MeV)} \times 10^{-45} \text{cm}^2.$$ calculated using the standard model (SM) of electroweak interactions. Although we make this comparison with the standard model, we prefer to check the standard model using our measured value of the interference term which we calculate in the next section.

Before the start of the 1996 run, targets A1 and A2 were removed and the A6 target was replaced by a new tungsten target. We calculated the cross
sections separately for the two different beam dump configurations, before (94–95) and after (96–97) the change:

\[
\sigma_{\nu_e e^-}^{(94-95)} = [11.3 \pm 2.0(stat.) \pm 1.3(syst.)] \times E_{\nu_e} \text{(MeV)} \times 10^{-45} \text{cm}^2
\]

\[
\sigma_{\nu_e e^-}^{(96-97)} = [12.0 \pm 3.0(stat.) \pm 1.7(syst.)] \times E_{\nu_e} \text{(MeV)} \times 10^{-45} \text{cm}^2
\]

These cross sections are very close in value to the cross section calculated using all the data.

8.6 Calculation of the Interference Term

The reaction

\[
\nu_e + e^- \rightarrow \nu_e + e^-
\]

can proceed through both charged current interactions and neutral current interactions. The standard model predicts a destructive interference effect between these two channels. In Chapter 1, Section 1.3.4 we defined a dimensionless interference term, \( I \), which indicates the strength of this interference effect. Here, we present the calculation of \( I \).

Let \( N^{\nu_e e^-} \) be the number of observed \( \nu_e e^- \) elastic scattering events and \( N^{CC} (N^{NC}) \) be the number of events one would expect had the reaction proceeded through only the charged current (neutral current) interaction. Denoting \( N^I \) as the number of events due to the interference effect and recalling the definition of \( \sigma^I \) in Chapter 1, Section 1.3.4, we have

\[
\sigma^{tot} = \sigma^{CC} + \sigma^I + \sigma^{NC},
\]

which implies
Table 8.8: The CC and NC Acceptances.

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\epsilon_{CC}$</td>
<td>0.121</td>
<td></td>
</tr>
<tr>
<td>$\epsilon_{NC}$</td>
<td>0.110</td>
<td></td>
</tr>
<tr>
<td>$\epsilon_{e^-e^-}$</td>
<td>0.120</td>
<td></td>
</tr>
</tbody>
</table>

\[ N^{\nu_e e^-} = \phi T (\epsilon_{CC} \sigma^{CC} + \epsilon_{CC} \sigma^I + \epsilon_{NC} \sigma^{NC}) \]
\[ = \lambda^{CC} + \lambda^I + \lambda^{NC}. \]

where we have used $\phi$ to denote the $\nu_e$ flux, $T$ to denote the number of target electrons and $\epsilon_{CC}$ ($\epsilon_{NC}$) to denote the acceptance had the reaction proceeded through only the charged current (neutral current) interaction.

We use the detector Monte Carlo simulation program to calculate these acceptance values. They are listed in Table 8.8 along with $\epsilon_{e^-e^-}$, the acceptance for the $\nu_e e^- e^-$ elastic scattering process. $\epsilon_{NC}$ is smaller than $\epsilon_{CC}$ because the recoil energy spectrum for electrons produced via the neutral current interaction is softer than that for electrons produced via the charged current interaction. We verify the value of $\epsilon_{NC}$ in a self-consistent way using the above expression of $N^{\nu_e e^-}$.

Thus we have

\[ N^I = N^{\nu_e e^-} - N^{CC} - N^{NC}. \]

Below, we calculate the various $N$ values and tabulate them (Table 8.9).

\[ N^{CC} = \phi T \epsilon_{CC} \sigma^{CC} = \phi T \epsilon_{CC} (4\sigma_0) \]

where, as before,

\[ \sigma_0 = \frac{G_F^2}{4\pi} E_{\nu_e}. \]
Table 8.9: The \( N \) Values.

<table>
<thead>
<tr>
<th>( N_{\nu e^\pm} )</th>
<th>133</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_{CC} )</td>
<td>201</td>
</tr>
<tr>
<td>( N^{NC} )</td>
<td>20</td>
</tr>
<tr>
<td>( N^I )</td>
<td>-88</td>
</tr>
</tbody>
</table>

\( \sigma^{NC} \) is same as the cross section for the reaction,

\[
\nu_\mu + e^- \rightarrow \nu_\mu + e^-.
\]

Using the value of this cross section in Table 8.1, we obtain

\[
\sigma^{NC} = 0.442\sigma_0
\]

and

\[
N^{NC} = \sigma T\epsilon_{NC}\sigma^{NC} = \sigma T\epsilon_{NC}(0.442\sigma_0).
\]

From Table 8.9 we obtain

\[
N^I = -88 \pm 22(\text{stat.}) \pm 11(\text{syst.}),
\]

where we have used the same 12% systematic uncertainty as in the cross section measurement. The interference coefficient, \( I \), is defined as

\[
I = \frac{\sigma^I}{2\sigma_0} = \frac{N^I}{2\sigma T\epsilon_{CC}\sigma_0}.
\]

Thus we obtain a value of

\[
I = -0.88 \pm 0.22(\text{stat.}) \pm 0.11(\text{syst.}).
\]

We observe that the measured interference term is unambiguously destructive, more than 3.5 standard-deviations from zero. It is within 1 standard-deviation from the value predicted by the standard model.
\[ I^{SM} = -1.08. \]

We have used \( \sin^2 \theta_W = 0.23 \) for the SM calculation. Also for comparison, experiment E225 measured an interference coefficient of

\[ I^{E225} = -1.07 \pm 0.17(\text{stat.}) \pm 0.11(\text{syst.}). \]

Finally, we can calculate a value for \( \sin^2 \theta_W \), where \( \theta_W \) is the Weinberg angle or the weak mixing angle of the standard model. For our analysis, we obtain

\[ \sin^2 \theta_W = 1/2 - I/4 = 0.28 \pm 0.06, \]

which should be compared to the SM value of 0.23.
CHAPTER 9

CONCLUSION

In this chapter we present a brief summary of the results. We then suggest some improvements for future analyses. Finally, we discuss the prospects of neutrino-electron elastic scattering measurements at ORLaND, a proposed neutrino experiment.

9.1 Summary of Results

From our final beam-excess sample of $228 \pm 19$ events, we attribute $95 \pm 10$ events to neutrino induced backgrounds thus obtaining $133 \pm 22$ events due to the $\nu_e e^- \rightarrow \nu_e e^-$ elastic scattering reaction. Using this number, we calculate a cross section of

$$\sigma_{\nu_e e^-} = [11.6 \pm 1.9(stat.) \pm 1.4(syst.)] \times E_{\nu_e}(\text{MeV}) \times 10^{-45}\text{cm}^2$$

for the $\nu_e e^- \rightarrow \nu_e e^-$ reaction. The average energy of the incident $\nu_e$ beam at LSND is 31.7 MeV.

This value is consistent, within errors, with a previous measurement by experiment E225 [39],

$$\sigma_{\nu_e e^-}^{E225} = [9.9 \pm 1.5(stat.) \pm 1.0(syst.)] \times E_{\nu_e}(\text{MeV}) \times 10^{-45}\text{cm}^2.$$

It also lies within 1 standard-deviation of the standard model value.

$$\sigma_{\nu_e e^-}^{SM} = 9.5 \times E_{\nu_e}(\text{MeV}) \times 10^{-45}\text{cm}^2.$$
The $\nu_e e^- \rightarrow \nu_e e^-$ reaction can proceed through both charged current and neutral current channels. The standard model of electroweak interactions predicts a destructive interference between the two channels. We calculate the strength of the interference effect.

$$I = -0.88 \pm 0.22({\text{stat.}}) \pm 0.11({\text{syst.}}).$$

This effect is unarguably destructive and is within 1 standard-deviation of the value predicted by the standard model.

$$I^{SM} = -1.08.$$

For comparison, experiment E225 has calculated a value of

$$I^{E225} = -1.07 \pm 0.17({\text{stat.}}) \pm 0.11({\text{syst.}}).$$

Finally, we calculate a value for $\theta_W$, the Weinberg angle or the weak mixing angle of the standard model. We measure

$$\sin^2 \theta_W = 0.28 \pm 0.06,$$

which also lies within 1 standard-deviation of 0.23, its currently accepted value.

### 9.2 Improvements for Future Analyses

Future analyses of the $\nu_e e^- \rightarrow \nu_e e^-$ reaction at LSND can hope to reduce both statistical and systematic errors in their cross section measurement. Let us discuss statistical errors first.

Fig. 9.1 shows the $\cos \Theta$ distribution for our final sample of beam-excess events. The same distribution for the beam-off sample is shown in Fig. 9.2.
Notice that the beam-excess events attributable to the elastic scattering process are bunched in the forward direction whereas the distribution for the beam-off events, which are produced by cosmic-ray interactions, is roughly flat. By making a tighter cut in $\cos \Theta$, one can reduce the CR background while only reducing the acceptance for the $\nu_e e^-$ elastic scattering process by a small amount. Thus by choosing a $\cos \Theta$ cut judiciously one can reduce the statistical error.

Figure 9.1: The $\cos \Theta$ distribution for the sample of beam-excess events. The expected distribution is shown by the shaded region.

The reason we do not make a tighter cut than $\cos \Theta > 0.9$ for the present analysis is that, currently, we rely only on the detector simulation to obtain our information about $\cos \Theta$. Although the expected $\cos \Theta$ distribution seems to describe the beam-excess events fairly well in Fig. 9.1, we choose a con-
Figure 9.2: The cos $\Theta$ distribution for beam-off cosmic-ray events.

A second event reconstruction procedure was used to analyse data for the DIF oscillation search [54, 55]. This procedure calculates the likelihood for the observed PMT charge and timing distribution as a function of event position, event direction and energy. The reconstruction values are provided by the set of those event parameters for which the likelihood function is maximized. This procedure is different from the current event reconstruction procedure which mainly relies on timing information from the PMTs. It is

servative cos $\Theta$ cut which lies well below the falling edge of the distribution. This limits our error in the acceptance for the cos $\Theta$ cut.

However, the LSND collaboration will eventually have a new independent check of the angle reconstruction procedure and thus a check of cos $\Theta$. A second event reconstruction procedure was used to analyse data for the DIF oscillation search [54, 55]. This procedure calculates the likelihood for the observed PMT charge and timing distribution as a function of event position, event direction and energy. The reconstruction values are provided by the set of those event parameters for which the likelihood function is maximized. This procedure is different from the current event reconstruction procedure which mainly relies on timing information from the PMTs. It is
thus hoped that the new reconstruction will provide an independent check of the current one. One can then compare the direction information from both reconstructions to gain a better understanding of $\cos \Theta$. Detector simulation studies using the new reconstruction, in fact, imply an improved angular resolution which could translate into a more sharply peaked $\cos \Theta$ distribution for the elastic scattering events.

Turning to systematic errors, we quote a 5.9% error in the acceptance of the $\text{dist}$ cut. The new reconstruction procedure could possibly shed some light on the "pushing out" effect described in Chapter 6, Section 6.5.1. This could hopefully lead to a lowering of this error. Also once the flux for 1996 and 1997 data is calculated using the modified beam Monte Carlo simulation program, the systematic error for the total flux calculation will be lowered from 7.5% quoted in our analysis to 7%. We expect that it will take one or two years to complete all these improvements.

9.3 Future Experiments

The Oak Ridge Large Neutrino Detector (ORLaND) collaboration is proposing a neutrino experiment at the newly proposed Spallation Neutron Source (SNS) at Oak Ridge National Laboratory. The proposed detector is larger than LSND and so is the expected neutrino flux. Thus the ORLaND collaboration hopes to collect approximately 100 times more data than LSND for the same time duration. This will allow one to measure the cross section for the $\nu_e e^- \rightarrow \nu_e e^-$ reaction with great statistical precision.

Also, more importantly, the fast beam spill at ORLaND allows one to separate neutrino-electron elastic scattering events due to the prompt $\nu_\mu$
flux ($N^\nu$) from those events due to a combination of $\nu_e$ and $\bar{\nu}_\mu$ ($N^\nu_e + N^\bar{\nu}_\mu$).

One can determine $\sin^2 \theta_W$ by measuring the ratio:

$$\frac{N^\nu_e}{N^\nu_e + N^\bar{\nu}_\mu}.$$

The accuracy of the $\sin^2 \theta_W$ calculation is then limited only by the statistical error in $N^\nu_e$ because, for the ratio, systematic errors in flux calculation and electron acceptance cancel. Also, due to fast beam timing one expects a negligible cosmic-ray background at ORLaND, allowing one to relax many of the cuts discussed here. The ORLaND collaboration expects to measure $\sin^2 \theta_W$ with an accuracy of better than 1%. This measurement compliments existing $\sin^2 \theta_W$ measurements as it is measured using purely leptonic processes at comparatively low transfers of momentum.
BIBLIOGRAPHY


APPENDIX

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Neville D. Wadia was born on May 21, 1970 in Bombay, India. He attended the Indian Institute of Technology, Kharagpur where he earned a bachelor of science (Hons.) degree in 1991 and a master of science degree in 1993, both in Physics.

He joined Louisiana State University in August 1993 for graduate studies in Physics. He was introduced to the LSND experiment at the Los Alamos National Laboratory in May 1994. He has been a collaborator on this experiment since then, working under the guidance of Professors Imlay and Metcalf.

In the Fall of 1998 he was awarded the degree of Doctor of Philosophy for his work on “Measurement of the Cross Section for Elastic Scattering of Electron Neutrinos on Electrons”. He is currently a Research Fellow at the University of Michigan, Ann Arbor.
DOCTORAL EXAMINATION AND DISSERTATION REPORT

Candidate: Neville D. Wadia

Major Field: Physics

Title of Dissertation: Measurement of the Cross Section for Elastic Scattering of Electron Neutrinos on Electrons

Approved:

Richard Gunley
Major Professor and Chairman

Dean of the Graduate School

EXAMINING COMMITTEE:

Date of Examination: September 30, 1998