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Search for neutrino oscillations at LAMPF

Timko, Mark, Ph.D.
The Ohio State University, 1987

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SEARCH FOR NEUTRINO OSCILLATIONS AT LAMPF

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
the Degree of Doctor of Philosophy in the Graduate
School of The Ohio State University

By

Mark Timko, B.S.

The Ohio State University

1987

Reading Committee:
Ta-Yung Ling
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Approved by

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Department of Physics
To my two children,

Matthew for bothering me while I wrote my thesis,
and Emily for staying out of the way.
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-my wife Marie, for giving up three years of her career to stay in Los Alamos and bear our two children.
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-Rick Miranda, who graduated too early and with a degree far below what his ulcer could tolerate.
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SEARCH FOR NEUTRINO OSCILLATIONS AT LAMPF

by

Mark Timko, Ph.D.
The Ohio State University, 1987
Professor Ta-Yung Ling, Advisor

The E645 experiment at Los Alamos is designed to search for the phenomenon of neutrino oscillations. The particular modes of oscillation searched for are: \( \bar{\nu}_\mu \rightarrow \bar{\nu}_e \) and \( \nu_e \rightarrow \bar{\nu}_e \).

The neutrino source is the LAMPF proton beam stop. The detector consists of 20 tons of liquid scintillator for particle calorimetry and proportional drift tubes for particle tracking. The \( \bar{\nu}_e \) detection mechanism employs the positron trigger that occurs from the \( \bar{\nu}_e \) inverse beta decay reaction on the free protons contained in the liquid scintillator (CH\(_2\)):

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

A preliminary data run was performed in the fall of 1986. The analysis showed that there were 0.04 (±0.6) beam induced events per LAMPF-day; a result that is consistent with zero oscillation events for the data run.

The null result confirms an excluded range of \( \sin^2 2\theta \) and \( \Delta m^2 \) values for a \( \bar{\nu}_\mu \rightarrow \bar{\nu}_e \) oscillation.
The E645 experiment can also uniquely rule out the exclusive $\nu_e \rightarrow \bar{\nu}_e$ oscillation process, which is expected if the $\nu_e$ is a Majorana neutrino. The 11.4 LAMPF-day run yields the only available limits on this oscillation process.
Chapter 1

Theory

The E645 experiment at LAMPF is concerned with observing a particular type of neutrino, namely the electron-antineutrino. The neutrino is a weakly interacting particle and, to detect a reasonable rate of its interactions with matter, it is necessary to have a large detector situated near an intense source of neutrinos. LAMPF provides such a scenario, in which the high current proton beam produces three types of neutrinos; the electron-neutrino ($\nu_e$), the muon-neutrino ($\nu_\mu$), and the muon-antineutrino ($\bar{\nu}_\mu$). To a good approximation, no electron-antineutrinos ($\bar{\nu}_e$) are created, and it is the goal of the experiment to search for the transformation (or oscillation) of one or more of the other three types of neutrinos into the electron-antineutrino.

This chapter outlines the history and characteristics of neutrinos. It describes the different types of neutrinos and the theoretical assumptions and mechanisms that allow one type of neutrino to oscillate into another type of neutrino. A brief survey of other published oscillation results is included to establish the merits of performing an oscillation experiment at the LAMPF beam stop.
1.1 Historical Establishment of the Neutrino

The concept of a new particle named neutrino was first proposed by Pauli in 1933\(^1\). In nuclear beta decay, of the type

\[ ^3\text{H} \rightarrow ^3\text{He} + e^- + \nu \]  

[1.1]

the new neutrino was needed to explain the experimentally observed behavior of the emitted electron. In general, this postulate of a three-body decay preserved the energy and momentum conservation axioms. In particular, Fermi in 1934\(^2\) showed that an electrically neutral, spin \(\frac{1}{2}\) particle with a zero rest mass could explain all the characteristics of beta decay.

In developing a theory for the neutrino, Fermi introduced a new force in nature which was termed the "weak force". It described the decay of a neutron into a proton, electron, and antineutrino,

\[ n \rightarrow p + e^- + \nu \]  

[1.2]

Since this process took a long time to occur in comparison to strong and electromagnetic reactions, a weaker coupling had to moderate the neutron decay, characterized by the constant \(G\). This constant has a value of \(1.03 \times 10^{-5}/m_p^2\) and is almost eight orders of magnitude smaller than the fine structure constant in electromagnetic interactions.

The matrix element which described the beta decay process was written by Fermi as
Each operator $O_i$, which creates the proton from the neutron in the hadronic current and produces the electron and neutrino in the lepton current, can transform as a scalar (S), a vector (V), a tensor (T), or an axial vector (A). The Fermi transitions of beta decay involve S and V operators, and the Gamow-Teller transitions involve A and T operators.

In 1948 the beta decay experiment of C. Sherwin, he measured the beta particle and the recoiling daughter nucleus and showed that, in order to conserve linear momentum, a third particle had to be emitted. However, the first direct physical evidence that such a neutrino actually existed occurred in 1953. In an experiment set up near a nuclear reactor, Reines and Cowan detected the antineutrino emitted from the reactor by the inverse beta decay reaction:

$$\bar{\nu} + p \rightarrow n + e^+.$$ [1.4]

During the middle 1950s, the weak interaction was the source of a conservation law crisis, typified by the "$\theta - \tau$ puzzle". The conservation law involved parity or reflection of the three spatial coordinates through the origin. In modern terms, the $K^+$ decays weakly into both a two pion state and a three pion state of opposite parity.
\[ K^+ \rightarrow \pi^+ \pi^0 \quad \text{(parity = +1), OR} \]
\[ K^+ \rightarrow \pi^+ \pi^- \quad \text{(parity = -1)} \]

This prompted Lee and Yang\(^6\) to postulate the violation of parity in the weak force, which was experimentally confirmed by Wu et. al.\(^7\) in 1957. The Wu experiment showed that, because of angular momentum conservation, the neutrino has a fixed helicity \(H\)

\[ H(\nu) = \frac{\hat{\sigma} \cdot \hat{p}}{|\hat{p}|} = \pm 1 \]

where \(\sigma\) is the spin of the neutrino and \(p\) is its momentum.

In 1958 Goldhaber et. al.\(^8\) explicitly showed that the helicity of the neutrino is -1, and similarly in 1969 Palathingal\(^9\) showed that the antineutrino's helicity is +1;

\[ H(\nu) = -1 \]
\[ H(\bar{\nu}) = +1 \]

This means that the neutrino is left-handed and the antineutrino is right-handed. Mathematically for neutrinos, the 4-component Dirac spinor used to describe spin 1/2 fermions could now be reduced to a 2-component spinor\(^10\). The other two states, the right-handed neutrino and the left-handed antineutrino, were forbidden by experiment, and therefore removed from the 2-component neutrino theory.

An alternative was to keep the 4-component Dirac spinor, along with a left-handed projection operator using the Dirac matrix \(\gamma_5\),

\[ \psi_L = \frac{1}{2} (1 - \gamma_5) \psi \]
These left-handed fields then permit only the vector and axial vector operators to remain; the scalar and tensor parts of the hadronic and leptonic currents become zero. Therefore, for the V-A phenomenological theory of weak interactions, the beta decay matrix elements for maximal parity violation can be written as

\[ M = \frac{G}{\sqrt{2}} \left( \overline{\psi} \gamma_\mu \left( 1 - \frac{C_A}{C_V} \gamma_5 \right) \psi \right) \cdot \left( \overline{\psi} \gamma_\mu \left( 1 - \gamma_5 \right) \psi \right) \]

where the vector coupling constant \( C_V \) is equal to one, and the axial vector coupling constant \( C_A \) is equal to -1.249 (±0.006). The Dirac matrices \( \gamma_\mu (\mu = 0, 1, 2, 3) \) and \( \gamma_5 \) are combined to form the exact representations for the V and A operators in the leptonic current and also to form an approximate V-A operator in the hadronic current.

In the modern Weinberg Salam Theory which unified the electromagnetic and the weak interactions, the older Fermi 4-point interaction diagrams (Fig. 1) are replaced by a propagator diagram with a massive weak vector boson, \( W^\pm \) (Fig. 2).

### 1.1.1 Lepton Flavor Conservation Law

The discovery that there existed different flavors of neutrinos came in 1962. Before then, only two charged leptons (e, \( \mu \)) and the neutrino, were known to exist. But the Brookhaven experiment of Danby et. al found that neutrinos produced in pion decay could only produce muons and not electrons:
Figure 1

Fermi 4-point interaction diagram of neutron beta decay.

Figure 2

Neutron beta decay schematic showing the intermediate vector boson ($W$).
\[ p^+ + \text{target} \rightarrow \pi^+ \rightarrow \mu^+ \nu \quad \text{and} \]
\[ \nu + \text{detector} \rightarrow \mu^+ + X \quad \text{(not } e^+) \quad \text{[1.10]} \]

The neutrinos must therefore be classified as electron-\((\nu_e)\) or muon-\((\nu_\mu)\) flavored neutrinos. Currently, the known lepton families are shown in Table 1. The Brookhaven experiment suggested a conservation scheme in which the lepton families retain their identity in physical reactions. The most common version is the additive lepton number conservation law\(^{13}\). It states that the sum of each lepton number \(L_e\), \(L_\mu\), and \(L_\tau\) for each flavor of lepton is the same before and after a physical process. Another version of a lepton number conservation rule is the multiplicative law\(^{14}\) in which the product of the muon parities for leptons, as assigned in Table 1, is the same before and after a reaction. As of 1986 the limits placed on these lepton numbers are shown in Table 1.

1.2 Neutrino Oscillations

In Section 1.1 a brief review of the currently accepted attributes of the neutrino is given. In summary they are:

1. the neutrino mass is zero,
2. the helicity of the neutrino (antineutrino) is exactly \(-1\) (\(+1\)),
   and
3. the neutrino takes part in lepton number conserving processes,
Table 1
Lepton Properties

<table>
<thead>
<tr>
<th>FLAVOR</th>
<th>PARTICLES</th>
<th>HELICITY</th>
<th>MASS</th>
<th>LEPTON FLAVOR NUMBER VIOLATION</th>
<th>ADDITIVE LEPTON NUMBER</th>
<th>MUON PARITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>e&lt;sup&gt;-&lt;/sup&gt;</td>
<td>-v/c</td>
<td>0.511 MeV</td>
<td>+1 0 0</td>
<td>+1 0 0</td>
<td>+1</td>
</tr>
<tr>
<td></td>
<td>ν&lt;sub&gt;e&lt;/sub&gt;</td>
<td>-1</td>
<td>&lt;500 eV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>e&lt;sup&gt;+&lt;/sup&gt;</td>
<td>+v/c</td>
<td>0.511 MeV</td>
<td>-1 0 0</td>
<td>+1 0 0</td>
<td>+1</td>
</tr>
<tr>
<td></td>
<td>ν&lt;sub&gt;e&lt;/sub&gt;</td>
<td>+1</td>
<td>&lt;50 eV&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Muon</td>
<td>μ&lt;sup&gt;-&lt;/sup&gt;</td>
<td>-v/c</td>
<td>105.7 MeV</td>
<td>μ + $\frac{ee}{Total}$ &lt; 1.7x10^-10</td>
<td>0 +1 0</td>
<td>-1</td>
</tr>
<tr>
<td></td>
<td>ν&lt;sub&gt;μ&lt;/sub&gt;</td>
<td>-1</td>
<td>&lt;250 keV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>μ&lt;sup&gt;+&lt;/sup&gt;</td>
<td>+v/c</td>
<td>105.7 MeV</td>
<td>μ + $\frac{3e}{Total}$ &lt; 2.4x10^-12</td>
<td>0 -1 0</td>
<td>-1</td>
</tr>
<tr>
<td></td>
<td>ν&lt;sub&gt;μ&lt;/sub&gt;</td>
<td>+1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tau</td>
<td>τ&lt;sup&gt;-&lt;/sup&gt;</td>
<td>-v/c</td>
<td>1784.2 MeV</td>
<td>τ + $\frac{YY}{Total}$ &lt; 5.5x10^-4</td>
<td>0 0 +1</td>
<td>+1</td>
</tr>
<tr>
<td></td>
<td>ν&lt;sub&gt;τ&lt;/sub&gt;</td>
<td>-1(?)</td>
<td>&lt;84 MeV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>τ&lt;sup&gt;+&lt;/sup&gt;</td>
<td>+v/c</td>
<td>1784.2 MeV</td>
<td>τ + $\frac{ey}{Total}$ &lt; 6.4x10^-4</td>
<td>0 0 -1</td>
<td>+1</td>
</tr>
<tr>
<td></td>
<td>ν&lt;sub&gt;τ&lt;/sub&gt;</td>
<td>+1(?)</td>
<td>&lt;84 MeV</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> Best non-preliminary and non-Lubimov result.
i.e. there exists three separate families of leptons.

This section describes the postulates of neutrino oscillations, and as a result, calls into question the three characteristics stated above.

The neutrino is a neutral spin 1/2 fermion that is separately distinct from its antiparticle, the antineutrino. It is therefore possible that an oscillation of the neutrino into the antineutrino could take place, in an analogous way to the $K^0$, $K^0$ oscillations well-known since the middle 1950s. In this context, Pontecorvo in 1957 first postulated the $\nu \neq \bar{\nu}$ oscillation idea\textsuperscript{15}. After the discovery of the $\nu_\mu$, Sakata\textsuperscript{16} and others\textsuperscript{17} proposed an oscillation scheme between different neutrino flavors, e.g. $\nu_e \neq \nu_\mu$.

There are only two theoretical impediments to neutrino oscillations. The first is a strict adherence to the lepton number conservation laws, and the second is a neutrino mass value of exactly zero. Either of these conditions will prevent the oscillation of neutrinos, yet the present experimental limits placed on each of the two impediments can still allow for an oscillation process to occur. For example, from Table 1 the mass of the $\nu_e$ is less than or equal to 40 eV, however, as will be seen later, the oscillation experiments are sensitive to a neutrino mass on the order of 1 eV. Also as an example, the best process to set a limit on lepton quantum numbers is the decay of a muon to an electron and a photon. This would violate the additive lepton number conservation scheme. The experimental limit placed on the $\mu^+ \rightarrow e^+\gamma$ decay rate\textsuperscript{18}, expressed in a ratio to the rate of $\mu^+$
decaying to all channels, is $1.7 \times 10^{-10}$. A theoretical calculation$^{19}$, assuming that the $\mu \rightarrow e\gamma$ decay occurred through an oscillation process, returns a limit on the branching ratio of $3 \times 10^{-26}$, well below any experimentally obtained values.

So, the best limits on lepton number conservation and on neutrino masses do not rule out the possibility that present experiments may be able to observe the oscillation process. Conversely, if in fact neutrinos do oscillate, this immediately implies that the mass of the neutrino is greater than zero. As a consequence, the helicity of the neutrino would not be fixed at -1, but would be equal to its velocity ($v$) divided by the speed of light ($c$),

$$H(\text{massive } v) = -\frac{v}{c} \quad [1.11]$$

where $|H| \leq 1$, i.e., a massive neutrino cannot travel at the speed of light. But the largest physical impact of massive neutrinos occurs for certain cosmological theories. There is astronomical evidence which indicates discrepancies between the rate of expansion of the universe and the amount of observable matter contained within the universe. This "dark matter" problem is also observed in the gravitational behavior of galaxies. The density of matter in the universe is calculated to be approximately $10^{-30}$ g/cm$^3$. Currently the neutrino density in the universe is estimated to be equal to the 3K blackbody photon density. Therefore it has an effective mass density on the order of $10^{-34}$ g/cm$^3$. If the total mass density of matter, radiation, and neutrinos reaches $2 \times 10^{-29}$ g/cm$^3$, the gravitational attraction of
the universe could halt its outward expansion. So, a mass of only 1 eV for the neutrino would be sufficient to cause the closing of the universe.

If neutrinos do oscillate, this also implies a violation of the lepton number conservation law. Processes such as $\mu \rightarrow e\gamma$ should occur, although for the two flavor oscillation case the limit is well beyond experimental access. However, certain theories in which the tau-neutrino is very massive can increase the $\mu \rightarrow e\gamma$ branching fraction limit to approximately $10^{-9}$.

1.3 Oscillation Mechanics

The theoretical formalism of neutrino oscillation is very simple and direct. It employs only time dependent quantum mechanics. Since the primary oscillation channel for E645 to detect is $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, only a two flavor neutrino oscillation theory is discussed.

The neutrino particle states that take part in the weak interaction processes, such as inverse beta decay, are the $\nu_\mu$ and the $\nu_e$ and their antiparticles. It is assumed that another representation of the neutrino can exist, namely the stationary particle states that have a definite and well defined mass, the $\nu_1$ and the $\nu_2$ and their antiparticles. These particles are eigenstates of the Hamiltonian

$$H |\nu_1\rangle = E_1 |\nu_1\rangle \quad i = 1, 2$$  \[1.12\]

where $E_i = [(p_i c)^2 + (m_i c^2)^2]^{1/2}$ and $m_i$ is the mass of the neutrino $\nu_i$. 
The weak interaction eigenstates and the mass eigenstates are grouped into two two-component states:

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu
\end{pmatrix}
\text{ weak interaction eigenstates}
\]

\[
\begin{pmatrix}
\nu_1 \\
\nu_2
\end{pmatrix}
\text{ mass eigenstates}
\]

[1.13]

With these assumptions it takes only a single free parameter to make the usual transformation between these basis states:

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu
\end{pmatrix} = U \begin{pmatrix}
\nu_1 \\
\nu_2
\end{pmatrix}
\]

[1.14]

where the unitary matrix \( U \) is given by

\[
U = \begin{pmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{pmatrix}
\]

[1.15]

where \( \theta \) is the neutrino mixing angle.

The time dependent quantum mechanical plane wave states for the \( \bar{\nu}_e \) is written as:

\[
|\bar{\nu}_e(t)\rangle = e^{iHt} |\bar{\nu}_e\rangle = \cos \theta e^{-iE_1 t/\hbar} |\nu_1\rangle + \sin \theta e^{iE_2 t/\hbar} |\nu_2\rangle
\]

[1.16]
The amplitude for finding a $\bar{\nu}_e$ at the time $t$ when the initial neutrino was a $\bar{\nu}_\mu$, is the dot product of the time dependent states $\langle \bar{\nu}_e(t) \rangle$ and $\langle \bar{\nu}_\mu(t=0) \rangle$:

$$\langle \bar{\nu}_e(t) | \bar{\nu}_\mu(0) \rangle = \cos \theta \sin \theta (e^{iE_1 t/\hbar} - e^{iE_2 t/\hbar})$$  \[1.17\]

The probability for finding a $\bar{\nu}_e$ is just the square of the amplitude:

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \cos^2 \theta \sin^2 \theta [2 - e^{i(E_1 - E_2) t/\hbar} - e^{-i(E_1 - E_2) t/\hbar}]$$  \[1.18\]

By using the following trigonometric relations:

$$\sin 2X = 2 \sin X \cdot \cos X$$
$$\cos X = (e^{iX} + e^{-iX})/2$$
$$\sin(X/2) = \pm \sqrt{(1 - \cos X)/2}$$  \[1.19\]

we can write the probability as

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \sin^2 2\theta \sin^2 [(E_1 - E_2) t/2\hbar].$$  \[1.20\]

Next a series of approximations are made:

1. the masses of the neutrinos are very small compared with their momentums; i.e. $m_i c^2 \ll p_i c$ and therefore the binomial expansion of the energies $E_i$ is used, keeping only the first order term;
2. the mass eigenstate neutrinos have the same momentum, i.e. $p_1 = p_2 = p_{\nu \mu}$.

3. the physical neutrinos have a very small mass, and therefore travel very nearly the speed of light. So, the time $t$ is equal to the quantity $L/c$ where $L$ is the distance traveled. Also the neutrino's momentum $p_{\nu \mu}c$ is approximately equal to its energy $E_{\nu \mu}$.

4. Note that $\hbar c = 197 \times 10^{-9} \text{eV m}$ and the energy is re-expressed in units of MeV.

Therefore the experimental appearance of a $\bar{\nu}_e$ oscillating from an original $\bar{\nu}_\mu$ is described by the probability equation

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \sin^2 2\theta \sin^2 \left(1.27 \delta m^2 \frac{L}{E}\right)$$

where $\delta m^2 \equiv |m_2^2 - m_1^2|$ is the mass eigenstate neutrino mass squared difference in units of eV$^2$, $L$ is the distance traveled in units of meters, and $E$ is the neutrino energy in units of MeV. Likewise, the disappearance of neutrinos is described by

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta \sin^2 \left(1.27 \delta m^2 \frac{L}{E}\right)$$.

Note that the theory has two free parameters, $\theta$ and $\delta m^2$ and the experimentally observed quantity $L/E$. Many types of experiments, all located at different values of $L/E$, will have different sensitivities to the oscillation process. For example, let three types of oscillation experiments be a solar neutrino, a reactor, and a beam dump.
experiment. Furthermore, let each be able to detect the oscillation process down to 10% of the no oscillation case, i.e. \( P(\nu_e \to \nu_e) \) and \( P(\bar{\nu}_\mu \to \bar{\nu}_e) \) are less than or equal to 0.1. Also assume that maximal mixing occurs, namely \( \theta \) is equal to \( \pi/4 \). From this ad-hoc setup, the three types of experiments will be able to set different limits on the parameter \( \delta m^2 \). Solar neutrino experiments try to detect neutrinos of energy 0.2 MeV that travel a distance of \( 5 \times 10^{10} \) m. This then gives them the ability to observe an oscillation result if \( \delta m^2 \) is greater than \( 10^{-12} \) eV\(^2\). Solar neutrino experiments afford the best opportunity to see neutrino oscillations so long as the neutrino producing theories correctly describe the number of higher energy neutrinos created in the core of the sun. Nuclear reactor experiments detect neutrinos of 5 MeV which travel a distance of 10 m. This gives them a \( \delta m^2 \) sensitivity down to 0.13 eV\(^2\). Here, however, the exact rate of neutrino production in the reactor core may not be known precisely. For the E645 experiment at LAMPF, the average neutrino energy is 37 MeV and the detector sits a distance of 26 m away from the beam stop. This provides a \( \delta m^2 \) sensitivity of around 0.58 eV\(^2\). Also, the LAMPF beam dump neutrino production rate is known very well.

This simplistic example shows that neutrino oscillation experiments are able to see a positive result for neutrino masses on the order of one eV/c\(^2\). Yet the real sensitivity of an experiment is a lot more complicated and depends on the inverse beta decay detection efficiency and on the electron-like backgrounds. The E645 sensitivities are dealt with in Chapter 2 and more extensively in the
The LAMPF beam stop, besides providing an intense source of neutrinos, offers other benefits as well. First, the neutrinos are produced from stopped pions and stopped muons as shown in Eqn. 2.1. Therefore, it produces low energy $\overline{\nu}_\mu$s well below the threshold for the charged current production of muons in the detector. Secondly, it provides a source of $\nu_e$s which, via the Majorana theory of the neutrino, could oscillate into $\overline{\nu}_e$s. Note that the theoretical equations for neutrino oscillation (Eqn. 1.21 and Eqn. 1.22) are valid for either the Dirac or the Majorana formulation of the neutrino. So, LAMPF also provides the opportunity for E645 to measure the $\nu_e \rightarrow \overline{\nu}_e$ oscillation channel as well as the $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillation mode.

The usual presentation of results or sensitivity limits of oscillation experiments are displayed on the $\sin^2 2\theta - \Delta m^2$ parameter space plot. The expected sensitivity for E645 is shown in Fig. 3. This curve was generated for 360 running days, with a negligible cosmic-ray background rate of 0.05 events per day. The details of the curve are described in the results of Chapter 6. Also shown in Fig. 3 are the published results of competing oscillation experiments. As can be seen, E645 has the ability to set the best limit on a $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillation process.
Neutrino oscillation sensitivity curves and results of some published experiments and a projected curve for E645.
Chapter 2

Experimental Introduction

The E645 experiment is made up of four major components:

1. An intense source of neutrinos from the LAMPF beam stop.
2. A large detector consisting of 18 tons of material, which provides the target protons with which the $\bar{\nu}_e$s can interact.
3. An active veto shield which completely surrounds the 18 ton central detector.
4. Shielding materials to block out two sources of background. One source is due to high energy neutrons from the beam stop. Besides the beam stop cavity shielding and 45 feet of tuff, 400 tons of extra steel is stacked in front of the detector to shield these beam neutrons. The other source is due to the neutral cosmic-ray particles, and to shield against these, 3300 tons of steel are piled over the detector.

Each of these elements of the experiment along with backgrounds to the inverse beta decay reaction are discussed in this chapter.

2.1 Beam Stop: the Neutrino Source

The Los Alamos Meson Physics Facility (LAMPF) generates and then accelerates an intense source of protons down a quarter mile long linear accelerator (linac). The energy of the protons reaches 800 MeV.
and the average current is approximately 1 mA as it leaves the linac. After a series of targets, which reduce the beam energy and intensity, the protons hit the A6 beam stop with an energy of 770 MeV and average current of 800 μA. At the nominal running conditions, these protons are accelerated in a 770 μs gate or beam "bucket". There are 120 buckets per second which implies a 9.2% duty cycle. The experiment is enabled to take data during this beam gate. Under new running conditions for the fall of 1986 (cycle 47), LAMPF was implementing an 80 Hz bucket rate or 6.5% duty cycle, while keeping the same number of protons on the beam stop (800 μA average current). This is a more favorable condition for E645 because, whatever cosmic-ray background may exist which would trigger the experiment within the beam gate, it is now reduced by one-third. The beam current is monitored via the "6ACM-1" counter and stored in the data buffer along with each event. This accumulated number is used to keep track of the number of protons that hit the beam stop and thus the number of neutrinos produced.

The actual intensity of neutrinos depends upon the exact beam stop configuration. There are three different materials in the path of the beam. They are (in the order that the beam hits them):

1. The water degrader, which causes a 20% increase\(^27\) in the neutrino output from just a copper beam stop alone.

2. The isotope production stringers, which are irradiated by the beam to create radioactive sources. This implies a slight time dependent neutrino flux, because the stringers are left in the
beam for different amounts of time and consist of different materials. The stringer information is also read into the computer so that the exact flux can be calculated.

3. The copper beam stop, which is a water cooled 0.3 m diameter by 1 m long cylinder that provides the final stopper for the beam.

The production of the neutrinos occurs through the $\pi$-$\mu$-$e$ decay chain

\[
P(800 \text{ MeV}) + \text{Cu (Beam stop)} \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \nu_\mu.
\]  \[2.1\]

These neutrinos are produced isotropically from the beam stop and have an energy between 0 and 52.8 MeV. The energy spectra are shown in Fig. 4. Calculations show\(^{28}\) that the nominal number of pions produced per incident proton is 0.079.

2.2 The Central Detector: The Target

The central detector was designed to produce and identify positrons from an inverse beta decay reaction,

\[
\bar{\nu}_e + p \rightarrow e^+ + n.
\]  \[2.2\]

The detector is segmented into forty layers, called "sub-modules". Each submodule consists of one plane of liquid scintillator tanks viewed by
Figure 4

The relative neutrino spectra produced from the LAMFF beam stop.
a photomultiplier tube (PMT) at each end, one plane of "X" proportional
drift tubes (PDTs), and one plane of "Y" PDTs (see Fig. 5). Gadolinium
Oxide ($\text{Gd}_2\text{O}_3$) painted sheets sandwich each scintillator plane on both
sides.

The target protons of Eqn. 2.2 are contained in the 15 tons of
liquid scintillator and three tons of the lucite containers. The
tracking of the positrons from the reaction 2.2 is accomplished via the
"X" and "Y" PDTs. The positron energy is reconstructed using the liquid
scintillator signals calibrated by cosmic-ray muons. The $\text{Gd}_2\text{O}_3$ sheets
are used in an attempt to observe the neutron from the reaction 2.2.

The number of free protons in the detector is equal to $1.60 \times 10^{30}$. The cross section for the $\bar{\nu}_e p$ inverse beta decay reaction for a
neutrino of energy 0 to 53 MeV averaged over the $\bar{\nu}_\mu$ spectrum from the
beam stop is $1.16 \times 10^{-40}$ cm$^2$. The triggering positron in reaction
2.2 is produced isotropically with an energy approximately the same as
that of the incoming neutrino. The fast electronics essentially
generates a trigger when the positron travels and hits three or more
scintillator planes (as in Fig. 5). So, this implies roughly a 50% detection efficiency due to the triggering geometry. With the nominal
beam current supplied at LAMPF, the flux of neutrinos out of the beam
stop is $3.4 \times 10^{19}$ neutrinos per LAMPF-day. If all the $\bar{\nu}_\mu$s oscillate
into $\bar{\nu}_e$s the expected number of inverse beta decay reaction events
detected at a distance of 26 m from the beam stop would be
$1.60 \times 10^{30} \times 1.16 \times 10^{-40} \times (3.4 \times 10^{19}/4\pi(2600)^2) \times 0.5$ which is equal to 37 per
LAMPF-day.
A small side view section of the central detector showing the scintillator tanks and PDTs (included is a visual example of the inverse beta decay reaction which serves as the neutrino oscillation signal for E645).
The maximum oscillation number gives a rough estimate of the limits that can be set on the two parameters $\sin^2 2\theta$ and $\delta m^2$. To do this, we must compare the maximum oscillation number with the number of positron-like events due to background. Let $N$ be the number of maximum oscillation events to which the detector is sensitive for a given run. If $B$ is the number of background events also detected in that run, then the statistical error or fluctuation in this number is simply $(B)^{1/2}$. Therefore the sensitivity of the experiment can be described by considering whether the value $N$ is more than just a statistical fluctuation of $B$; i.e. is the probability for oscillation $P$ larger than the ratio $(B)^{1/2}/N$. The 90% confident limits on the probability $P$ are stated as an inequality:

$$ P \leq 1.65 \frac{\sqrt{B}}{N} \quad \text{(2.3)} $$

That is, $P$ would have to be smaller than this ratio, otherwise $N$ would be 1.65 standard deviations beyond the background $B$. The oscillation equation of Chapter 1 is

$$ P = \sin^2 2\theta \sin^2(1.275\delta m^2 \frac{L}{E}) \quad \text{(2.4)} $$

We can approximate this equation for two cases: case 1 is a high $\delta m^2$ limit, and case 2 is a low $\delta m^2$ limit. For case 1, $\delta m^2$ is very large and over the length of the detector many oscillations occur. This implies that the term $\sin^2(1.27 \delta m^2 L/E)$ averages to the value 1/2.
Therefore Eqn. 2.4 becomes

\[ p = \frac{\sin^2 2\theta}{2} \quad \text{as } \delta m^2 \to \infty . \tag{2.5} \]

For case 2, \( \delta m^2 \) is very small and the term \( \sin^2(1.27 \cdot \delta m^2 \cdot L/E) \) approaches the argument \( (1.27 \cdot \delta m^2 L/E)^2 \). Therefore, Eqn. 2.2 becomes:

\[ p = \sin^2 2\theta \left( \frac{1.27 \cdot \delta m^2 L}{E} \right)^2 \quad \text{as } \delta m^2 \to 0 . \tag{2.6} \]

If we were not to see any \( \bar{\nu} e \) signal at all, and yet assume a \( \bar{\nu} e \) signal could exist within the statistical fluctuations of the background events (ignoring for a moment the random and systematic errors of the detector), we would set limits on \( \sin^2(2\theta) \) and \( \delta m^2 \) in the above two cases. For case 1 we get a crude 90\% confidence limit on \( \sin^2(2\theta) \) by using Eqn. 2.3 and Eqn. 2.5. Assuming that the run took place for 180 days with 0.1 background events per LAMPF-day, we have:

\[ \sin^2 2\theta \leq \frac{2 \cdot 1.65 \cdot \sqrt{18}}{6660} = 0.0021 . \tag{2.7} \]

For case 2 we use Eqn. 2.3 and Eqn. 2.6 and assume that we have "maximal" oscillations, i.e. \( \theta = \pi/4 \) or \( \sin^2(2\theta) = 1 \). This gives a crude limit on \( \delta m^2 \), for an average \( \bar{\nu}_e \) energy of 37 MeV, and for the distance of 26 m from the beam stop. Therefore we have,
\[ \delta m^2 \leq \left[ \frac{1.65}{6660} \right]^2 \cdot \frac{37}{(1.27 \cdot 26)} = 0.036. \] 

This is the approximate sensitivity of E645 given the above assumptions. A more detailed sensitivity curve, seen in Fig. 3 in Chapter 1, is described in the likelihood fit in Chapter 6.

The positron (e\(^+\) from Eqn. 2.2) is our primary \( \overline{\nu}_e \) signal. However, the energy of that positron is very similar to that of a positron or electron produced from a stopped, cosmic-ray muon. In order to observe these possible stopped muons, a "history" of the detector is needed. The electronics does this by recording the detector signals up to 56 µs before the positron trigger. Secondly, a slow neutron process occurs if the neutron (from Eqn. 2.2) becomes thermalized. The mylar sheets, brushed with paint doped with gadolinium-oxide (Gd\(_2\)O\(_3\)), were added to the detector so that the thermalized neutron would be captured by a gadolinium nucleus. This capture results in up to four photons, of 8 MeV total energy, emitted by the excited \( Gd \) nucleus. The photons are detected in the scintillator via Compton scattering. About 40% of the neutrons thermalize within the detector volume in a time of 110 µs. Hence, the detector signals are also being recorded for up to 110 µs after the positron trigger. Therefore, the electronics views a total "time window" of 166 µs for every event (Fig. 6). The details of this data recording by the electronics is described in Chapter 3.
Figure 6

The electronic time window employed in the storage of data for the central detector and active veto shield.
2.3. Active Veto

The veto shield was designed to completely cover the central detector and provide two modes of shielding.

1. Active veto: A liquid scintillator layer viewed by about 360 PMTs to veto and detect charged particles which may enter the central detector.

2. Passive veto: Seven inches of lead shot, with a 60% packing fraction, is equivalent to five inches of solid lead. This amounts to 24 radiation lengths of material and attenuates photons produced by cosmic-ray muon bremsstrahlung or stopped muons decaying to electrons which may bremsstrahlung; all this occurs outside the active veto shield.

The 360 PMTs are cabled to electronics which is described in more detail in the next chapter. The net effect is to provide on-line vetoes generated when muons pass through the liquid scintillator. A "SHORT VETO" of 3 μs is generated when a muon enters and exits the shield, whereas a "LONG VETO" of 11 μs occurs when a muon enters, but no exit point is seen by the PMTs.

These vetoes amount to approximately 13.5% dead time and their inefficiency is approximately $4 \times 10^{-4}$. The measured effect of the veto is reflected in the vetoed trigger rate of the central detector. That rate is reduced from 2000 Hz for no veto to a 1 Hz vetoed average trigger rate. Within a 9.2% duty cycle beam gate, this gives a 0.1 Hz
data taking rate.

The active veto shield PMT pulses are also recorded for a total time window of 154 μs, using a system similar to the central detector electronics (Fig. 6). When the events are replayed off-line, the recorded pulses can provide a "software" veto capability. This reduces the number of muon related triggers by an approximate factor of $6 \times 10^3$. This implies an overall hardware and software veto inefficiency of about $6 \times 10^{-7}$.

The shield "off-line" veto is also used in the search for stopped muon events. The muon in the past, that entered and stopped in the detector prior to the 11 μs "LONG VETO", can also be observed in the shield data history.

2.4 Cosmic-Ray Background and Shielding

The cosmic rays at a given depth below the top of the atmosphere consist of two components: a hadronic component and a muon component. At sea level the charged cosmic-ray flux is 180 particles per meter-squared per second, but comprises only 19% of both the myonic and hadronic cosmic rays. The neutral particles make up the other 81%. Los Alamos is about 7300 feet above sea level and has a charged cosmic-ray flux of about 185 particles/m²-s. Because there is only 800 gm/cm² of material (air) between this altitude and the top of the atmosphere, the hadrons make up 95% of the total cosmic-ray rate, while the muons make up only 5% of the total. This large hadronic component, comprised mainly of neutrons, would cause various types of background for the
experiment. Since the neutron attenuation length is about 200 g/cm$^2$, extra shielding of about 2000 g/cm$^2$ is required to reduce the neutral flux through the central detector to an acceptable level. This will, to a lesser extent, also reduce the charged component flux seen by the central detector. Shown in Fig. 7 is a plot of the cosmic-ray flux in arbitrary units versus shielding$^{30}$ in units of g/cm$^2$ (curve a).

Note, the zero shielding point is the top of the atmosphere. Up to the 800 g/cm$^2$ point, the shielding is only air. Beyond this point the extra shielding is mostly steel, with a little "tuff" (a soft compressed volcanic ash that forms the mesas around Los Alamos).

As of November, 1986 there was approximately 3300 tons of steel stacked up over the detector tunnel (Fig. 8). This amounts to 2000 g/cm$^2$ of extra shielding directly overhead. Note that in Fig. 9 the shielding tapers off on the sides. This is because the flux of higher energy cosmic-ray neutrons is strongly peaked in the vertical direction$^{31}$. A Monte Carlo simulation$^{32}$ has shown that only about 1500 g/cm$^2$ are needed ten feet beyond the sides of the central detector to effectively attenuate these higher energy cosmic-ray neutrons. The planned overburden for the July, 1987 run is 3000 g/cm$^2$ (4000 tons), which is based upon a neutral cosmic-ray measurement in an underground tunnel near the Los Alamos Laboratory shown in Fig. 7 (curve b). The two curves of Fig. 7 cannot be reasonably connected. However, the tunnel measurement illustrates that an extra 3000 g/cm$^2$ will sufficiently attenuate the cosmic-ray neutrons; the bend in curve b is not due to cosmic-ray neutrons, but is due to secondary neutrons.
Figure 7

Cosmic-ray flux as a function of shielding and a cosmic-ray measurement conducted at Los Alamos.
Figure 8

Elevation view of the LAMPF neutrino area tunnel and the E645 detector.
Figure 9

End view of LAMPF neutrino area tunnel and the E645 detector.
induced from muon interactions in the surrounding rock.

Closing up the tunnel is a 24 foot diameter by 20 foot long cylinder filled with water. This provides approximately 730 gm/cm\(^2\) of shielding at the back of the detector. A three foot diameter passageway exists as an entrance to the electronics hut.

The experimental effects of the charged cosmic rays fall into two categories:

1. Direct: "through" muons or stopped muons actually entering into the central detector and
2. Indirect: mainly photons produced by muon or electron bremsstrahlung.

The direct muons are vetoed by the active veto shield. The "SHORT VETO" provides on-line rejection against through muons, while the "LONG VETO" rejects stopped muons. Any muons that are not vetoed on-line can be eliminated off-line by using the digitizer electronics.

The indirect processes occur mostly outside of the active veto shield. Cosmic-ray muons which miss the veto shield may produce bremsstrahlung. These photons could enter the detector and pair produce, thereby triggering the experiment with electrons and positrons. Also, muons which stop and decay in the tunnel or tuff produce electrons also giving bremsstrahlung which can travel into the central detector. The total number of photons from these sources that could enter the central detector is estimated to be about 19 x 10\(^4\) per LAMPF-day\(^3\). To take care of this background, there are 24 radiation
lengths of lead stored on the inside of the active veto shield. The fraction of photons leaking through the steel and the lead is $1.5 \times 10^{-6}$, thereby reducing this external entry rate to 0.03 events per LAMPF-day.

The neutral component of cosmic rays is responsible for five basic reactions. These reactions can cause experimental triggers, either directly in the central detector or indirectly, by creating secondary particles which then enter the central detector. The five reactions are listed below, including the approximate cross sections in millibarns for 200 MeV incident neutrons along with the particles that can actually cause the trigger.

1. neutron-proton elastic scattering: $n^{12C} \rightarrow p^{12B}$ ($\sigma \approx 185$ mb), $np \rightarrow np$ ($\sigma \approx 40$ mb). The knock on proton is produced in the central detector and may travel three or more planes. Most of the protons can be eliminated by a total energy cut.

2. neutral pion production: $n^{12C} \rightarrow n^{013N}$, $np \rightarrow npe^+e^-$, $n^0 \rightarrow \gamma\gamma \rightarrow e^+e^-$. The $n^0$ decays into two photons which can pair produce. The resulting $e^+e^-$ will trigger and will give positron type events in the experiment. These pions can be created inside the central detector or outside of the central detector, namely, in the last interaction length of the inside of the passive shield. These photons then enter the central detector and convert into the $e^+e^-$ pair.
3. Charged pion production: $n^{12}_C \rightarrow \pi^{-13}_N$, $n^{12}_C \rightarrow \pi^{+13}_B$, $np \rightarrow p\pi^-$, and $np \rightarrow n\pi^+ + \pi^-$. The $\pi^-$ is captured and absorbed by nuclei or free protons. The $\pi^+$ decays into a muon and the muon decays into an electron which can then trigger the experiment. The pions which are created inside the central detector can also trigger the detector themselves.

4. Photon production: $n^{12}_C \rightarrow n^{12}_C* \rightarrow n'\gamma^{12}_C$ ($\sigma \approx 7$ mb). These are lower energy photons emitted in this reaction. There exists a negligible amount of higher energy photons which can convert into a triggerable electron-positron pair in the central detector.

5. Spalation (nuclear breakup): $n^{12}_C \rightarrow n'\alpha$ ($\sigma \approx 21$ mb). This effect would not cause a single particle track, but may produce a triggerable "splat" in the detector.

These types of reactions can be successfully eliminated only by shielding against the incoming cosmic-ray neutrons.

2.5 Beam Associated Background and Shielding

The beam associated backgrounds of the $\bar{\nu}_e$ oscillation signal involve two particles produced at the beam stop; electron neutrinos ($\nu_e$) and neutrons ($n^0$). It is critically important that we either shield against these backgrounds or understand their significance, because it is the beam excess electron-type events that will determine whether or not we see an oscillation phenomenon. These two types of backgrounds are discussed next.
The $\nu_e$s produced from the beam stop pass through the central detector and interact with nuclei such as $^{12}$C, $^{13}$C, $^{16}$O, and $^{27}$Al, or with "free" electrons in the atoms and molecules of the detector. We cannot shield against these $\nu_e$s so we must calculate their effect on the data.

2.5.1 $\nu_e$ Carbon-12 Reaction:

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

The average cross section $\sigma$ for this reaction is $35 \times 1.46 \times 10^{-41}$ cm$^2$ and the number of $^{12}$C nuclei $N(^{12}\text{C})$ in the central detector's physical volume is $0.822 \times 10^{30}$. The energy distribution of the electrons produced is shown in Fig. 10 and shows a maximum electron energy of 35 MeV instead of 53 MeV since the Q value of the reaction is 18 MeV.

With a lower energy cut of 25 MeV, 50% of the events are removed. The emitted electrons are peaked in the backward direction with respect to the incident neutrino, but the angular acceptance for the trigger can be taken to be 50%. The total detection efficiency $\eta$ is therefore 25% for this reaction. The average rate for the detection of this $\nu_e^{12}$C background is with a neutrino flux of $4.0 \times 10^{11}$ $\nu_e$ per squared-centimeter per LAMPF-day:

$$\text{RATE} = \nu_e \text{flux} \cdot N(^{12}\text{C}) \cdot \sigma \cdot \eta = 1.2 \text{ events per LAMPF-day.}$$ \[2.9\]

To eliminate this background a 35 MeV cut is necessary.
Figure 10

Relative event distributions of $\nu_e$ induced backgrounds.
2.5.2 $\nu_e -$ electron elastic scattering:

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

The cross section $\sigma$ for 32 MeV neutrinos incident on this reaction is\(^{36} 2.87 \times 10^{-43} \text{ cm}^2 \), and the number of "free" electrons $N(e^-)$ in the central detector's fiducial volume is $7.6 \times 10^{30}$. The energy distribution of the electrons, shown in Fig. 10, indicates a maximum energy of 50 MeV. With a 20 MeV threshold, 67% of the events are removed. Also the electron is peaked in the forward, or $\nu_e$ direction, very strongly. This implies an angular acceptance for detection of about 60%. This makes the total trigger efficiency equal to 20%. The rate of this background is then 0.17 events per LAMPF-day.

2.5.3 $\nu_e -$ Oxygen-16 Reaction:

$$\nu_e + ^{16}O \rightarrow e^- + ^{16}F$$

The estimated average cross section for this reaction is\(^{37} 0.52 \times 10^{-41} \text{ cm}^2 \). The number of oxygen nuclei contained in the lucite and cardboard of the central detector is $0.13 \times 10^{30}$. With a trigger efficiency of 25%, similar to the $\nu_e^{12}C$ reaction; the rate of electrons produced is 0.07 events per LAMPF-day.
2.5.4 $\nu_\ell$ - Carbon-13 Reaction:

$$\nu_\ell + ^{13}\text{C} \rightarrow e^- + ^{12}\text{N}^*$$

The cross section for this reaction is approximated for a neutrino energy of 32.2 MeV as $6.0 \times 10^{-41}$ cm$^2$. The number of $^{13}\text{C}$ nuclei due to its natural abundance of 1.1% is $0.9 \times 10^{27}$. With a trigger efficiency of 50%, the rate of this reaction is a negligible 0.01 events per LAMPF-day.

2.5.5 Other $\nu_\ell$ - Nuclei Interactions

The above reactions account for most of the potential positron background in the data. The $\nu_\ell - ^{27}\text{Al}$ rate is 0.06 events per LAMPF-day produced from the ten kilograms of the aluminum in the cardboard PDTs. The $\nu_\ell - \text{Gd}$ rate is not known, but there should be no problem with the gadolinium used in the slow neutron detection experiment.

2.5.6 Beam Excess neutrons

There exists an enormous high energy neutron flux emanating from the beam stop. This is because approximately one fast $n^0$ is created per incident proton. These neutrons, of energy 100 MeV or greater, induce electron type triggers similar to the cosmic-ray neutron background discussed in Section 2.4.

The energy distribution of the neutrons obeys the power law $E_n^{-1.8}$. These fast neutrons are distributed in a forward cone centered around the beam line with the apex at the beam stop. The intensity of
neutrons at the surface of a particular cone falls off as an exponential function proportional to $e^{-\theta/17^o}$, where $\theta$ is the polar angle from the beam center line to the surface of the cone. The center of the detector sits at a polar angle of only $12^o$ from the beam center line, and therefore the neutron intensity is only reduced by a factor of 0.5. A Monte Carlo estimate gives approximately a 25 Hz rate of neutrons entering the detector, with a 2 Hz rate for neutrons greater than 200 MeV. This was seen July 12, 1986; our first look at the beam. This made clear the need to attenuate these neutrons by piling up steel at the front of the tunnel, between the beam stop and the detector. This was done and an 80% reduction in beam excess triggers was observed. However, there still existed a large number of neutron induced triggers and this plagued the rest of the fall, 1986 engineering run.
Chapter 3

Apparatus

The E645 central detector consists of a layered arrangement of forty scintillator planes and 41 "X" and "Y" wire chambers. An active veto shield completely surrounds the central detector (see Fig. 11). Below are explanations of the various components.

3.1 Proportional Drift Tubes (PDTs)

The "X" and "Y" coordinates of a charged track in the detector are measured using low mass, cardboard proportional drift tubes (PDTs). The cardboard is used as the wall support of the cells of the PDTs. This is a creative alternative to the standard aluminum walled wire chambers, and is used to minimize the beam $\nu_e$ background from the reaction $\nu_e + ^{27}$Al $\rightarrow e^- + ^{27}$Si. Each two mil wire is contained in a gas filled cell 1.5 inches thick, 3 inches high and 12 feet long.

There are 45 wires in a PDT plane, grouped into five nine-banks (Fig. 12). The PDT submodule arrangement is simply five nine-banks held vertically (for "X") and five nine-banks held horizontally (for "Y"). Therefore, both the "X" and "Y" planes are mounted on a single frame, each 90° with respect to the other (Fig. 12). The gas used is called P-10, which is 90% argon and 10% methane. It is put in through one end of a nine-bank, zigzagging through the nine cells, and exhausted at the other end.
Figure 11

The E645 detector drawing showing the central detector on its own cart and the surrounding active veto shield.
Figure 12

An expanded view of one submodule of the central detector.
A high voltage of 1950 Volts is applied on one end of the nine wires, while the signal is pre-amplified at the other end. The small negative signal from a wire, produced by a passing charged particle, is inverted and stretched by the preamps whose current gains are approximately equal to 20. Eighty feet of unshielded ribbon cable connect the preamp to the electronic readout module. The ribbon's 34 wires are assigned different functions. The most important are the +12 V and -12 V lines, which supply power to the preamp, and the signal lines that carry the preamp output. Any two signal lines are separated by two ground lines to avoid excessive crosstalk. The five, 80 foot long ribbons from a PDT plane are routed into the electronics hut and plugged into five channels (or groups) of a single width FASTBUS sized card called a digitizer.

3.2 Scintillators

The energy loss of a charged track in the detector is observed using plastic lucite tanks filled with liquid scintillator and viewed on each end with a photo multiplier tube (PMT). Each tank is 1.25 inches (3 cm) thick, one foot high, and 12 feet long. Twelve such tanks, hung horizontally with straps fastened by "Velcro" , comprise a scintillator plane (Fig. 12).

The extruded lucite tanks have a rib glued down the middle of their entire length to prevent hydrostatic bulging when filled with eight gallons of liquid scintillator. In earlier prototype modules the bulge caused stress on the rounded corners of the tank. The
pseudo-cumene in the liquid scintillator is known to cause micro-fractures of lucite when the lucite is under stress\textsuperscript{41}. These prototypes would then crack and the scintillator would all leak out, taking anywhere from one day to one month\textsuperscript{42}. The ribs solved this problem, and only three out of 480 tanks cracked in 18 months.

Plastic endcaps were glued on each end of the scintillator tank. Attached to the north endcaps were the fill and drain hoses. In the middle of each endcap is a Hamamatsu R878 PMT. This ten stage tube runs at approximately 1300 V and provides a current amplification of \(10^6\). This PMT was tested along with several other two inch tubes\textsuperscript{43} and chosen because of its good photo cathode efficiency of approximately 28\% and a low singles rate of approximately 100 Hz. The rather poor timing resolution of about 10 nanoseconds (ns), full-width at baseline, was not an important consideration. The combination of good quantum efficiency and Bicron's 517L liquid scintillator provides approximately fifty photoelectrons for a minimum ionizing cosmic ray at the center of the tank.

The PMT output is carried over 70 feet of RG-58 coax-cable to a module called a shaper. The 12 south and 12 north PMTs from a scintillator plane plug into the 24 inputs of the shaper (Fig. 13). The shaper provides a two line fanout of the signal. One fanout direction has the 12 south and 12 north lines with gains of one. These signals are carried over shielded ribbon coax-cables to the FAST LOGIC modules (described in Section 3.8). The other fanout direction inverts and stretches the small negative PMT pulse, with a current gain of 16, in a
A schematic drawing of the shaper module.
method similar to the PDT preamps. These 24 PMT shaped outputs of a single shaper are carried by three ribbon cables and plug into three channels of a digitizer card. Both the ribbon cables and the digitizer cards are of the same type used for the PDTs.

3.3 Digitizers

The pulses of the PMTs and PDTs from the central detector are recorded in the digitizer electronics. Below, some of the digitizer's features are described.

The first feature of the digitizer electronics is the large 166 microsecond (μs) time window per event. This is accomplished by using a flash ADC (FADC) chip clocked every 81.3 ns (clock frequency = 12.5 MHz), and having the digital output stored in a 2K (2048) memory (2048 * 81.3 = 166 μs). This large clock period of 81 ns is the reason that the PMT and PDT pulses are stretched. The pulse inversion is needed because this is a position voltage FADC.

The signals travelling through the whole system are shaped for a full-width at baseline of 1 μs. This gives about 15 digital samples per pulse, with 3 to 4 samples on the leading edge. Timing is calculated for points on the leading edge and energy loss is measured by the pulse height and/or pulse area.

It is also desirable to measure a large range of visible signals. The primary particles we wish to detect are positrons, and this sets the lower part of the dynamic range needed. There will also be protons detected (and eliminated), and these protons, at the end of
their range, can lose up to 15 times the energy of positrons. This fact determines an upper limit needed for the digitizer dynamic range. To accommodate this large range in energy loss, we employ a bi-level FADC system. That is, there are two 6-bit FADCs with different input gains. The lower FADC, which outputs a number from 0 to 63, has an extra gain of eight on its input. This FADC is set to have a dynamic range from 0 to 2 times the signal obtained from a minimum ionizing particle. That is, the minimum ionizing cosmic-ray muon signal is set at channel 35. The higher FADC, which outputs a number from 64 to 127, covers a dynamic range of 2 to 15 times minimum ionizing and is enabled when the lower channel FADC overflows. So, the positrons are measured with the smaller range, higher resolution FADC (#1); while the protons are measured with the larger range, lower resolution FADC (#2). A figure of voltage input and FADC output value shows this bi-level system (Fig. 14). Note that the ratio of the slope of FADC #1 to the slope of FADC #2 is equal to the extra gain of eight.

The second feature of the digitizer system is implemented because of the need to economize on the number of FADCs used (the price of each was 30 dollars for the RCA CA 3300E). In this system every PMT and every wire does not have its own FADC and memory channel. We linearly add the pulses from the nine signal lines of a ribbon cable and feed the sum into one FADC memory channel (Fig. 15) We also use discriminators to flag which of the nine wires have signals on them; a discriminator bit is turned on if that wire (S-1 through S-9) was hit.
The flash ADC (FADC) response to an input linear voltage ramp.
Figure 15
A schematic diagram of the central detector's FASTBUS digitizer card.
The discriminator threshold is set to 10 mV which is equivalent to a FADC value between channels 2 and 3 of the low FADC #1.

For the PDTs, the nine wires of the nine-bank utilize all the nine signal lines of the ribbon and digitizer system. Whereas, for the PMTs, only S-1 through S-8 are used. The S-9 lines for the PMTs are grounded at the shaper.

The entire central detector is instrumented with a total of 106 digitizer cards in five FASTBUS crates. The scintillator’s 960 PMTs plug into forty shapers. With three ribbon cables per shaper and five ribbon cables per digitizer card, the PMTs use approximately 24 cards total. The PDTs have 3690 wires, from 410 nine-banks. With one ribbon per preamp, and five ribbons per card, the PDTs use 82 digitizer cards.

When the digitizers are in the data taking mode, the clock simply runs, cycling over the 2K of memory. When a trigger occurs, the clock continues running for 110 μs, then stops. This therefore leaves 56 μs of history before the event. The data from the central detector are then stored in the digitizer’s memories. Each 16 bit memory word has the lower seven bits for the FADC digital output, while the higher nine bits are for the discriminator mask. The readout of these memories is performed by a micro-code programmable engine called a "controller".
3.4 Controller

The controller is a double-width FASTBUS module that controls the running of each crate. Its basic features are:

1. **Parallel_readout.** All five groups of a card are read out in parallel to the controller.

2. **Test_for_above_threshold_ADC_data.** This reduces the 250,000 possible words of the digitizer cards in a crate.

3. **Processing.** It assigns a time and address to the data.

4. **Concatinate_signals.** Reformating of the data into pulses provides a three to one compression in the event size.

5. **LAM_control.** When all five crates are done with the above steps, they are then read out through CAMAC.

Each controller consists of a control memory to store a microcode program, readout hardware to test for and move data from the digitizer cards, a data memory to store the raw data, and an Arithmetic and Logical Unit (ALU or processor) chip to rework the raw data into pulses.

The control memory is an 88-bit word x 1K RAM, with each bit or group of bits controlling some hardware aspect of the controller. First, it drives the digitizer electronics to take data by passing the 12.5 MHz clock to the crate and allowing the digitizer memories to store data. After a trigger occurs, the microcode then loads a pre-set
compaction threshold value into a comparator chip. The threshold used is equal to four channels of the low channel (0 to 63) FADC #1. Any digital data lower than this value are ignored, since most of the digitizer memory contains either no data at all or electronic noise below channel 4.

The controller reads out one card at a time. The 7-bit ADC data from for all five groups of that card, are moved in parallel and latched in a register (Fig. 16). If any group contains an ADC value above or equal to channel four, an interrupt occurs, which signals the microcode to store the ADC value in an ALU register. The microcode then reads out the 9-bit discriminator mask for that group and stores it in a second ALU register. Next, the microcode labels the location, from where the data comes, in a third ALU register. That word is an address built up from a crate number, slot number, and group number, and is called the "I.D.". Finally the data are assigned a "time", which is just the digitizer memory location, and this word is stored in a fourth register. These four words are then moved into a 12 bit x 4K (4096) RAM called the data memory. This four word format continues until all the groups of all the cards in a crate are read out.

Note that each ADC sample of a pulse carries along three extra words. This is repeated and unnecessary information which is eliminated by a pulse concatenation routine in the microcode. The routine passes over the raw data to reformat the event into "pulses". These pulses are stored in the unused portions of the data memory. The time, I.D. tag and mask are written once, then the adjacent ADC values
Figure 16

A schematic diagram of the central detector's FASTBUS controller.
are concatenated in the data memory. This is called the pulse format and it results in a 3 to 1 compression of the data. Also the event size is variable. Therefore, the pulse routine puts in the necessary pointers (indices) and lengths, so that the data are fully described for an off-line program. When the pulse building is done, the four word format is ignored, and only the pulse format is read out to CAMAC.

So, the data compaction involves two microcode routines. Each crate contains 22 cards and there are five groups per card. With 2K words per group, this involves 225,000 possible words. Yet the first level compaction typically reads out only about 200 to 400 words of above-threshold data within the 170 µs time window. The four word format is therefore 1000 to 1500 words long in the data memory. With the pulse format microcode, this size is reduced further and only about 300 to 500 words per crate are read out to CAMAC.

3.5 Readout to CAMAC

When the execution of the pulse format routine is completed, the controller sends out a readout done signal (TTL level). A five fold coincidence of these signals, one from each of the five crates, generates a computer interrupt (CAMAC LAM). The PDP-11 then begins the controller data memory readout. This is done one crate at a time, in sequential order from crate one to crate five. When the CAMAC transfer is complete, the microcode goes back to data taking mode, waiting for the next event.
A special feature is used when the event size is very large. If there were too much data in the digitizer memories, and the four word format microcode completely filled the 4K data memory, there would be no room left for the pulse format routine to use. In this case, the event is read out to CAMAC in the four word format, and the microcode continues the digitizer readout. This digitizer readout, CAMAC readout cycle continues until all the digitizer cards in a crate are read out. This is called a "FLUSHED" event and implies an infinite readout of the central detector. An off-line fortran program can then replicate the pulse-format microcode to convert the four word data into pulses.

The PDP-11 reads the data from CAMAC and sends it to a VAX-750 via an all-purpose communication link (DEC DR-11W with Fermilab CD: drivers). The PDP-11 readout program has two 5000 word buffers in its memory and uses one of these buffers to read out from CAMAC. When that buffer is filled, it sends the data to the VAX while the second buffer picks up the CAMAC readout. This continues until the VAX has the entire event written to magnetic tape.

3.6 Active Veto Shield Digitizer Electronics

The active veto electronics employs a similar method of digitization. Each of the 360 PMTs are carried over by 120 feet of RG-58 BNC coaxial cable. Sixteen PMTs plug into one single-width FASTBUS card. In the card the signal is inverted, stretched, and fed into one 6-bit FADC (RCA CA330CE). There is no multiplexing (sharing) of the PMT inputs as with the central detector electronics (Fig. 17).
Figure 17

A schematic diagram of the active veto shield's FASTBUS digitizer card.
The pulse is digitized every 150 ns and stored into a 1K memory. This provides a 154 μs time window for the active veto shield. The shield digitizer electronics has a controller that is not microprogram controlled. Upon a trigger, the controller reads out four memory channels (quad) in parallel and keeps all four channels' contents if any one of them is above a preset threshold (set to one FADC value). The four, 6-bit values are stored in one 24-bit word of the data memory. At that time, an address consisting of a slot number, quad number, and time or memory location are combined into one, 24-bit word of the address memory. When the compaction is complete the CAMAC program interrogates a "compaction done bit" sent from the controller; there is no LAM for the shield digitizer CAMAC readout.

The shield controller toggles between the data memory and the address memory, sending these 24-bit words over CAMAC, into the 5K buffer of the PDP-11 program. The average shield event size is about 2000 to 3000 16-bit words.

3.7 Trigger Logic and Electronics and Veto

As stated earlier, the 12 PMTs on the south side of a scintillator plane are carried from the shaper module over a 26 pin coax ribbon and input into a single width FASTBUS sized, FAST LOGIC card. Each PMT has its own channel. The 12 north PMTs of the same plane are input into 12 different channels on that same FAST LOGIC card. The pulses are discriminated and are latched in a register. The discriminator threshold is 8 mV. This corresponds to about 0.5 MeV of
energy loss or a 0.1 minimum ionizing particle and is equivalent to channel 3 of the digitizer FADCs.

The job of the fast logic is to test for two specific hit conditions among the 12 south and 12 north PMTs of that plane. The two conditions are:

1. "OR" One PMT is hit out of the 24 total.
2. "AND" Both the south and north PMTs are hit on a single scintillator tank.

This testing is done every 250 ns (clock frequency = 4 MHz). So the entire scintillator PMT hits in the central detector are reduced to two bits per plane: one "OR" bit and one "AND" bit. Note if an "AND" exists an "OR" also exists. These "AND" and "OR" signals are taken into a trigger module, which does the triggering of the central detector based on the number and the locations of the scintillator planes being hit.

3.8 Trigger Module

The trigger module consists of 13 memory chips, each is a 4K by one bit RAM. The eighty "AND" and "OR" signals address these chips. If a "1" were loaded into the word addressed, the chip outputs a "1", or trigger. If a "0" were loaded into the word addressed, the chip outputs a "0", or no trigger.
For example, let's take the first six planes of the detector. The first six planes address the first of the memory chips, with the "OR" of plane 1 in address line 1, the "AND" of plane 1 in address line 2, the "OR" of plane 2 in address line 3, etc. (Fig. 18). Suppose a particle track caused 3 "AND"s in planes 3, 4, and 5 (also 3 "OR"s for planes 3, 4, and 5) and "0" for all other planes (planes 1, 2, and 6). If planes 3, 4, and 5 had "AND"s (and therefore "OR"s), the address would be (in bits) 00111110000, or 3F0 hex, which is equal to memory location 1008. Since this is an acceptable pattern for triggering, a "1" in memory location 1008 of that chip would be loaded and conversely, if it were not an acceptable condition, a "0" would be loaded. This addressing process takes place every 250 ns. So, in general a pattern is made up for every acceptable triggering condition and those memory locations which would be addressed by such a condition are loaded with a "1". All other locations are zero.

The experiment was designed to trigger on any four adjacent planes hit by a charged track. To get this, an overlapped pattern of memory chips is used. Planes 4 through 9 are input into the second memory chip (Fig. 18). Because there is an overlap of three planes, here planes 4, 5, and 6 are in chip 1 and in chip 2, any four adjacent planes will trigger. For example, if the four planes were 3, 4, 5, and 6, chip 1 would trigger. If the four planes were 4, 5, 6, and 7, chip 2 would trigger. This 3 plane overlap continues for the entire forty planes and results in a total of 13 chips.
Figure 18

A schematic diagram of some channels of the trigger processor module.
So the triggering design is based on instrumenting groups of six planes into one memory chip. The trigger condition desired is any three "AND"s out of a 6-plane group or memory chip. This is different than any three "AND"s out of any six adjacent planes, but the effects of these boundary conditions are negligible. For example, a trigger pattern consisting of any three planes per memory chip, gives an instantaneous trigger rate of 18 Hz. Whereas, a trigger pattern consisting of three planes out of any four adjacent planes, which is not subject to this boundary problem, gives a rate of 17 Hz. Therefore, this systematic error can be neglected.

However, at present this "3-AND" pattern has a very high trigger rate of 18 Hz and is probably due to the neutral component of cosmic rays (because 2000 gm/cm$^2$ of our overburden is not sufficient to shield these neutrals). Therefore the data reported here were triggered requiring a four "AND" out of a six-plane group, which gave a raw instantaneous trigger rate of about 1.0 Hz (a factor of 20 less).

3.9 Veto

Along with the trigger module testing for a trigger pattern, the active veto shield electronics is testing for a veto condition. This veto is then input into the trigger module and prevents the occurrence of an "EVENT" trigger.

The main purpose of the veto is to prevent a trigger from a cosmic-ray muon that passes through the detector. This muon would make its transition in 100 to 500 ns. Therefore, a short veto of 1 to 2 µs
is necessary to veto a "through" muon. Another possibility is a cosmic-ray muon which stops in the detector and later decays, resulting in an electron that would trigger the experiment. So, a long veto of 10 to 20 μs is necessary to veto this process.

To accomplish this long and short veto, the entire shield is broken up electronically into three segments (Fig. 11):

1. The cylinder and west wall, which together have a total 252 PMTs on them,
2. The east wall, which has 46 PMTs, and
3. The cart (or bottom) which has 64 PMTs.

Each part of the electronics which services a segment is loaded with a multiplicity value, that is, a number between 0 and 15. If the number of PMTs in that segment are greater than or equal to the multiplicity value, a veto is generated. For example, the cylinder's multiplicity value is five. If any five out of the 252 PMTs are hit, a veto is produced. The east wall's multiplicity value is 4 and the bottom's multiplicity value is 3. This is called a 5-4-3 multiplicity condition for the cylinder, east wall, and bottom segments respectively.

If two of the three segments are hit, as with a cosmic-ray muon that passes through the detector, a short veto of 3 μs is generated. If only one segment is hit, as with a stopped muon, a long veto is generated. This veto testing is done every 150 ns (clock frequency = 6.667 MHz). Note also that a "through" cosmic-ray muon could hit only one segment (especially the cylinder) and it would produce a long
veto. A Monte Carlo\textsuperscript{44} has shown that approximately one-half of all through muons will generate a long veto. This increases the veto dead time only by 4\% for a 11 \( \mu \)s long veto.

One veto signal of variable length (long or short veto) is then carried over to the trigger module and will veto the central detector. This signal is updated, i.e., if another stopped muon hits the shield within the 11 \( \mu \)s long veto, the shield controller will issue another 11 \( \mu \)s long veto. The overall veto dead time is 13.5\% for 2000 g/cm\(^2\) of overburden, a 5-4-3 multiplicity, and a 11 \( \mu \)s long veto. The trigger module rate then goes from 2000 Hz (unvetoed) to 1 Hz (vetoed) for a four "AND" trigger pattern.

In summary, Fig. 19 is a schematic representation of the trigger-veto process:

1. The scintillator PMTs give signals due to particles.
2. The fast logic turns the scintillator PMT signals into "AND"s and "OR"s for each of the forty planes.
3. The trigger module takes the forty "AND"s and "OR"s and tests for an acceptable trigger condition.
4. The active veto shield PMTs give signals to charged particles passing through its six inches of scintillator.
5. Every 150 ns a long or short veto is tested for.
6. If this veto exists while a trigger occurs, the central detector trigger is blocked and no experiment trigger is generated.
Figure 19

An overview of the trigger and veto scheme used in the experiment.
Chapter 4
Detector Calibration

4.1 Basic Efficiency

The first step taken in understanding the central detector was measuring the efficiencies of the FAST LOGIC modules, scintillator PMTs, and PDT wires. These efficiency measurements used the FAST LOGIC and digitizer signals obtained from through-going, cosmic-ray muons.

The data were collected in seven segments across the entire detector. Only one segment at a time was enabled to accept a trigger and the other segments were disabled, by loading the appropriate pattern in the trigger module. The first level trigger pattern was a "4-AND" condition to obtain shallow angle cosmic rays. The second level trigger pattern was used to segment the detector (Table 2). Note the overlap of the planes of the detector. These overlapped trigger patterns ensured minimal bias in the measured efficiencies of the scintillator planes which also participated in the trigger.

4.2 Efficiency Analysis

The cosmic-ray muon that passed through the detector was tracked using the PDTs. Therefore, its path through a particular scintillator tank or PDT nine-bank was known. The digitizer signal or FAST LOGIC bit was then examined to see if that PMT, wire, or FAST LOGIC channel had above zero data. The ratio of the number of tracks observed to the
Table 2

The cosmic ray calibration procedure across seven segments of the central detector.

<table>
<thead>
<tr>
<th>CENTRAL DETECTOR SEGMENT NUMBER</th>
<th>FIRST LEVEL MEMORY PATTERN</th>
<th>SECOND LEVEL MEMORY PATTERN (PLANES ENABLED)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>&quot;4-AND&quot;</td>
<td>1-9</td>
</tr>
<tr>
<td>2</td>
<td>&quot;4-AND&quot;</td>
<td>1-15</td>
</tr>
<tr>
<td>3</td>
<td>&quot;4-AND&quot;</td>
<td>7-29</td>
</tr>
<tr>
<td>4</td>
<td>&quot;4-AND&quot;</td>
<td>13-27</td>
</tr>
<tr>
<td>5</td>
<td>&quot;4-AND&quot;</td>
<td>19-31</td>
</tr>
<tr>
<td>6</td>
<td>&quot;4-AND&quot;</td>
<td>27-39</td>
</tr>
<tr>
<td>7</td>
<td>&quot;3-AND&quot;</td>
<td>31-40</td>
</tr>
</tbody>
</table>

a) The "4-AND" pattern allows shallow angle muons to trigger.
number of tracks through a device was calculated for the measured efficiency. For the scintillators, five efficiencies using the digitizer signals were measured per plane:

1. **PMT**: 24 efficiencies, one per PMT. The PMT fired for a cosmic ray through its tank.

2. **Tank AND**: 12 efficiencies, one per tank. Both south and north PMTs fired for a cosmic ray through that tank.

3. **Tank OR**: 12 efficiencies, one per tank. A south or north PMT fired for a cosmic ray through that tank.

4. **Plane AND**: 1 efficiency, one per plane. One tank (both south and north PMTs) fired for a cosmic ray through that plane.

5. **Plane OR**: 1 efficiency, one per plane. One PMT fired for cosmic ray through that plane.

Shown in Fig. 20 through Fig. 24 are all five efficiency plots for the 960 PMTs, the 480 tanks, and the forty scintillator planes.

For the PDTs, two efficiencies using the digitizer signals were measured per plane:

1. **Bank**: 5 efficiencies, one per nine-bank. One of the nine wires fired for a cosmic ray through that nine-bank.

2. **Plane**: 1 efficiency, one per plane. One of the 45 wires fired for a cosmic ray through that plane.

Both efficiency plots for the 400 nine-banks and the eighty (40 "X" and
Figure 20

Histogram of digitizer efficiencies for 960 scintillator PMTs.

Figure 21

Histogram of digitizer "AND" efficiencies for 480 scintillator tanks.
Figure 22

Histogram of digitizer "OR" efficiencies for 480 scintillator tanks.

Figure 23

Histogram of digitizer "AND" efficiencies for 40 scintillator planes.
Figure 24

Histogram of digitizer "OR" efficiencies for 40 scintillator planes.
40 "Y") PDT planes are shown in Fig. 25 and Fig. 26.

For the FAST LOGIC modules, five efficiencies of the scintillators were measured per plane:

1. OR: 24 efficiencies, one per PMT. One PMT fired for a cosmic ray through its tank.

2. Tank AND: 12 efficiencies, one per tank. One tank (both sought and north PMTs) fired for a cosmic ray through that tank.

3. Tank OR: 12 efficiencies, one per tank. A south or north PMT fired for a cosmic ray through that tank.

4. Plane AND: 1 efficiency, one per plane. One of 12 tanks fired for a cosmic ray through its tank.

5. Plane OR: 1 efficiency, one per plane. One of 24 PMTs fired for a cosmic ray through its tank.

All five efficiency plots for the 960 PMTs, the 480 tanks, and the forty scintillator planes are shown in Fig. 27 through Fig. 31.

The FAST LOGIC threshold is on the average similar to the threshold of the digitizer data, and a crosscheck on the FAST LOGIC modules was performed. If the digitizer saw a visible signal for a cosmic ray, the FAST LOGIC may also have seen that PMT signal. A plot of the efficiency of the FAST LOGIC tank "AND" divided by the digitizer tank "AND" (Fig. 32) reveals this fact, as the distribution peaks significantly around one.
Figure 25
Histogram of digitizer efficiencies for 410 PDT nine-banks.

Figure 26
Histogram of digitizer efficiencies for 82 PDT planes.
Figure 27

Histogram of fast logic efficiencies for 960 scintillator PMTs.

Figure 28

Histogram of fast logic "AND" efficiencies for 480 scintillator tanks.
Figure 29

Histogram of fast logic "OR" efficiencies for 480 scintillator tanks.

Figure 30

Histogram of fast logic "AND" efficiencies for 40 scintillator planes.
**Figure 31**

Histogram of fast logic "OR" efficiencies for 40 scintillator planes.

**Figure 32**

Histogram of the ratio of the fast logic tank "AND" efficiency divided by the digitizer tank "AND" efficiency.
4.3 Detector Calibration

Besides the obvious diagnostic benefits, the basic aim of the detector calibration was to reconstruct the energy of the particles in the detector. This was done by using cosmic-ray muons only. A muon which traversed the detector was tracked using the PDTs, and its "X" and "Y" coordinates as well as the angle through each scintillator tank was calculated with a track fitting routine. Most muons which passed through three centimeters of scintillator lost 5.6 MeV of energy, thereby giving a visible signal in the PMTs. This signal followed a standard Landau distribution for energy loss.

First there is a correction of the pulse height of the visible signal for angle, thereby treating all tracks as if they were at normal incidence to the scintillator tank. Secondly, the south PMT pulse height is divided by the north PMT pulse height. Shown in Fig. 33 is the logarithm of this ratio versus the location of the track in the scintillator tank. The linearity of the plot indicates an exponential attenuation of light in the scintillator, as expected. The band in Fig. 33 is narrow, since the Landau tail due to an actual electron or delta ray knocked out of the scintillator molecule is divided out in taking this ratio. Tracks close to the PMT were removed to eliminate the $1/r^2$ component. A fit of the slope to this distribution gives the attenuation length for each tank, and Fig. 34 shows a plot of these attenuation length values for all 480 tanks.
Figure 33

Attenuation length plot for scintillator plane 3, tank 9.

Figure 34

Histogram of attenuation lengths for 480 scintillator tanks.
A second pass over the same data is performed to obtain a normalization constant for each PMT. Again, the pulse height is corrected for the angle of the track. The distance from the track to each PMT is known. So, the attenuation lengths obtained beforehand are used to correct the pulse height of each PMT, thereby treating the tracks as if they were in the center of the scintillator tank. The visible signal is then Landau distributed in a histogram and the peak is found. This peak is called the "muon-peak" and represents the expected energy loss (5.6 MeV) for a normally incident muon passing through the center of the scintillator tank. After a series of voltage adjustments and data taking, the desired peak position can be set. The corrected pulse height plot for a single PMT is shown in Fig. 35, and the distribution of "muon-peaks" for all 960 PMTs is shown in Fig. 36. As can be seen, we tried to set the "muon-peaks" at digitizer channel 35.

These constants are then saved and used in off-line programs. Each PMT visible signal is converted to an energy, via a formula

$$E_{\text{VISIBLE}} = \frac{\text{VISIBLE SIGNAL}}{\text{MUON PEAK}} \cdot 5.6 \text{ MeV} \quad [4.1]$$

4.4 PDTs

No real voltage adjustments were made to the PDTs; all nine-banks are supplied the same voltage of 1950 V. However, each nine-bank has a "muon-peak" constant. Particles lose much less energy
Figure 35

Pulse area plot for PDT plane 32, bank 4.

Figure 36

Histogram of pulse areas for 410 PDT nine-banks.
in the PDT gas than in the scintillator planes, so the PDT signals are not used in the calculation of energy loss. Yet these PDT "muon-peak" constants can be used to identify particles by their energy deposition in the gas.

The scintillator PMT "muon-peaks" employed in the energy conversion formula (Eqn. 4.1) uses the actual height of the digitized pulse. The pulse height is used since the signal generation in the PMTs, which converts photons into electrons is a very fast process. But, for the PDTs, the signal is generated by the wire collection of drift-electrons in the gas. This process can take up to two microseconds and can result in a pulse that is wider and lower than a PMT signal. So, for the PDTs, the pulse area rather than the pulse height is a better representation of the energy loss of the charged track. The trapezoidal rule is used in the algorithm for the pulse area calculation.

The distribution of the PDT pulse area corrected for the track angle for a single nine-bank is shown in Fig. 37. Note that the signals from all nine wires are plotted and show a fair amount of uniformity among the nine cells. A plot of all 410 nine-banks (Fig. 38) shows that the nine-banks are also fairly uniform with respect to each other.

The values of the PDT "muon-peaks" are also saved and used in the off-line program to identify the signals that come from each nine-bank. The algorithm used is described in Chapter 6.
Figure 37

Pulse height plot for the south PMT of scintillator plane 3, tank 9.

Figure 38

Histogram of pulse heights, or "muon-peaks", for 960 scintillator PMTs.
4.5 Stopped Muons

The scintillator PMT "muon-peaks", derived from "through" cosmic-ray muons, are the only means of energy conversion used. A good way to test this calibration procedure is to reconstruct the energy of electrons that come from decayed, stopped muons.

To obtain a set of electrons from stopped muons, a special trigger is used. It requires a coincidence between the active veto shield and the detector. Recall that if a stopped muon is detected by the shield, it produces a "LONG VETO". This "LONG VETO" would then be presented at the trigger module, and no experiment trigger would occur. However a special output was installed on the trigger module that gives out a signal if the detector is hit independent of the state of the veto. This signal is called "DET-OUT" and stands for detector out. A logical AND of "DET-OUT" and "LONG VETO" is therefore a possible stopped muon inside the shield that has also hit the detector. This produces a 10 μs gate which is then used to enable the trigger module. If the stopped muon decays within the standard triggering acceptance of the detector, the electron will then trigger the trigger module, and the event is read out. This scheme gives an electron enriched data set; about 50% of triggers are good electrons inside the fiducial volume of the central detector. This data set can then be used to test the energy calibration of the entire detector. The following quantities are measured:
1. The time difference between the incoming muon and the electron. This gives a measurement of the 2.2 μs lifetime of the muon. The time distribution is shown in Fig. 39 and gives an actual measured lifetime of 2.14 μs.

2. The angle difference between the muon and electron (Fig. 40).

3. The electron energy reconstruction which consists of three parts:
   
   3.1. The visible energy deposited in scintillator tanks by the electron track,
   3.2. The energy loss (dead energy) in the inactive material in between the scintillator tanks, and
   3.3. The associated energy due to the electron bremsstrahlung. These photons Compton scatter in other scintillator tanks and give small amounts of visible signal. They are defined as any scintillator tank that is hit in the detector within 1 μs of the electron track, excluding the track itself. An example of a stopped muon with a bremsstrahlung hit is shown in Fig. 41.

The distributions of these three energies are shown in Fig. 42 through Fig. 46 along with an EGS45 Monte Carlo46 along with the track and total energy events passed through the same energy algorithms.

The dead energy is defined as a fraction of the visible energy and is calculated by using the number of "dead" and "live" regions traversed by the particle. The formula is:
Figure 39

Histogram of electron and muon time difference for stopped muon data.

Figure 40

Histogram of the electron and muon cosine angle difference for stopped muon data.
Figure 41

Graphics display of the E645 detector showing an electron which decayed from a stopped muon that entered the detector 4 μs earlier.
Figure 42

The visible energy of stopped muon electrons and the EGS Monte Carlo results.

Figure 43

The "dead" energy estimate for stopped muon electrons and the EGS Monte Carlo results.
Figure 44

The energy calculated for stopped muon electron tracks (visible plus dead energies) and the EGS Monte Carlo results.

Figure 45

The associated energy for stopped muon electrons due to bremsstrahlung and the EGS Monte Carlo results.
The total energy (visible plus dead plus associated energies) for stopped muon electrons and the EGS Monte Carlo result.
\[
E_{\text{DEAD}} = E_{\text{VISIBLE}} \cdot \left( \frac{\text{number of "dead" regions}}{\text{number of "live" regions}} \right) \cdot \left( \frac{\text{fractional energy loss in a "dead" area}}{\text{fractional energy loss in a "live" area}} \right). \quad [4.2]
\]

As defined, this dead energy can never overestimate the positron's true energy loss in the dead area.

The associated energy is sometimes difficult to reconstruct because the distance from the Compton scattered electron to the PMT is not known precisely. Therefore there are large errors in correcting for the attenuation length if only one PMT on that tank is hit. If, however, both PMTs are hit within a single tank, the energy is as accurate as a passing muon through that tank. A random trigger data set was taken and compared to the stopped muon data set to get the effect of noise on the associated energy algorithm. It shows that in the beam gate only 13.3\% (±1.1\%) of the associated events are due to the PMT singles rate, with 95.4\% of those hits depositing between 0 and 1 MeV of total energy. In the cosmic-ray gate only 8.3\% (±0.56\%) of the associated events are due to the PMT singles rate, with 97.2\% of these events having an energy between 0 and 1 MeV. This indicates that the beam on running conditions have twice the noise rate as the cosmic-ray gate data, yet the contribution is a small percentage of the electron associated energy as plotted in Fig. 45.

The fairly good agreement between the Monte Carlo and the real stopped muon data allows one to trust the Monte Carlo in other aspects
of the calibration. Specifically, mono-energetic positrons at 40 MeV were generated at different angles in the detector and the energy was reconstructed using exactly the same energy algorithms. The total energy is plotted in Fig. 47 and shows an energy shift of approximately five MeV. The energy spread is approximately ±9% and, this uncertainty will be taken into account in the final likelihood fit in Chapter 6.

4.6 Detector Response

As can be seen for the 40 MeV electrons plotted in Fig. 47, there is a five MeV shift in the reconstructed total energy. This effect is also seen from the electron Monte Carlo and the real data comparison (Fig. 42 through Fig. 46), in which the electron energy distribution does not exactly match a perfect Michel spectrum. Some of this difference can be explained by the energy resolution of the detector. However, a more important effect is that some of the positron's energy was not accounted for due to bremsstrahlung leaving the detector. The overall shift of approximately five MeV is in fact due to photons carrying energy out of the detector. But, whatever the causes, in general there may exist a redistribution of the detector's reconstructed energy. This difference between the "input" and "output" spectrums must be taken into account, and this detector "response" effect is incorporated into the final likelihood calculation of the $\sin^2\theta - 5m^2$ plot in Chapter 6.
Figure 47
Histogram of the total energy reconstructed for Monte Carlo electrons after being passed through an EGS and a "4-AND" trigger simulation program.

Figure 48
Histogram of the total energy for Monte Carlo electrons (Michel spectrum) from 20 to 53 MeV.
4.7 Trigger Efficiency

At the present time, the Monte Carlo is the only way to obtain an estimate of the efficiency of the central detector's trigger processor. The procedure is described in this section. A set of Monte Carlo electrons is generated inside the detector with a Michel energy spectrum (Fig. 48). These data are then passed through a trigger processor simulation program, which searches for a "4-AND" hit configuration in the scintillator tanks. The output energy spectrum from this program is shown in Fig. 49 and gives an overall "4-AND" efficiency is 20.8% for detecting stopped muon electrons of energy 20 MeV or greater. The overall "4-AND" efficiency for electrons between 0 and 53 MeV is 19.2%. Note that the Monte Carlo assumes a 100% efficiency for the scintillator tanks' PMTs. A crude correction can be made by multiplying the average FAST LOGIC tank "AND" efficiency of 88.7% (see Fig. 28). This then reduces the stopped muon electrons' overall "4-AND" triggering efficiency to 17.0%.
Figure 49

Histogram of the total energy for Monte Carlo electrons after being passed through a "4-AND" simulation program.
Chapter 5

Data and Analysis

The basic aim of this experiment is to find the positron emitted in the inverse beta decay reaction:

\[ \bar{\nu}_e + p \to e^+ + n \]  

[5.1]

where the \( \bar{\nu}_e \) can arise only from the oscillation of a \( \bar{\nu}_\mu \) (or a \( \nu_e \)) produced in the beam stop.

The software analysis was written primarily to identify electrons, or electron-type events, in the data. In addition, the analysis was also useful in identifying and eliminating backgrounds to the positron signal. It should be noted that this is a very preliminary analysis and that at the time of writing, it is only eight man-month's old. Yet, because of the very simple nature of the experiment, such a preliminary analysis can accomplish a great deal.

The detector's relatively thin, 3 cm scintillator tanks and low mass PDTs were designed to measure low energy electrons from 20 to 50 MeV. An electron traversing one scintillator tank and one "X" and one "Y" PDT plane (i.e. one submodule) loses approximately 8 MeV of energy. This was established in the January, 1984 beam test\(^4\). Particle identification for this test that used only the total visible energy from the scintillator PMT signals, showed that electrons and protons could be reasonably distinguished from one another. A beam of
40 MeV electrons was injected into a mock-up of the central detector at normal incidence (0°) to the scintillator tanks. A test beam of 189 MeV protons was also injected at normal incidence to the scintillator tanks. The total energy, measured for those tracks that traversed three submodules, is plotted in Fig. 50. It is seen that there is a clean separation of these two types of particles. That is, only 0.8% of the protons had a small total energy loss in the scintillator which overlaps with the 1% tail of the electron energy distribution. An energy loss versus track length plot also shows a high degree of separation between electrons and protons (Fig. 51).

Present data taking conditions also reveal "electron" type and "proton" type tracks (see Fig. 52 and 53). These "proton" type tracks are defined as the higher energy loss events and are due to protons or kaons produced from neutron interactions. The "electron" type tracks are defined as the lower energy loss events and are due to electrons, electron-positron pairs produced from photons, muons, pions, or protons which may clip the corners of a scintillator tank and therefore be incorrectly identified as electrons. If an oscillation signal is to be found from the data, the analysis must find as many positron tracks as possible from the "electron" type data set.

In addition to using the total visible energy reconstruction, many other parameters of the event are calculated and tested. In summary, the analysis is performed according to the following outline:

1. Active shield "software" veto,
Figure 50

Histogram of the visible energy for electron and proton tracks with a track length equal to three scintillator tanks (beam test data).

Figure 51

Visible energy versus track length plot for electrons and protons (beam test data).
Figure 52

Histogram of visible energy for tracked events in the detector that occurred while the beam was on.

Figure 53

Visible energy versus track length plot of tracked events for beam gated data.
2. Track finder and fitter (to a straight line).

3. Fiducial volume cut.

4. Energy reconstruction and tests;
   4.1. Visible energy cut of 53 MeV,
   4.2. Energy versus track length cut, and
   4.3. Differential energy loss or "dE/dx" algorithms, which tests
       the energy lost per scintillator tank and compares it to the
       energy lost by true electrons.

5. Stopped muon cut, which finds a stopped muon type track in the past
   that was spatially near the triggering particle, and

6. Hand scan of the events which passed the above cuts.

Each of these cuts is described in detail in the remainder of this chapter.

5.1 Active_Shield_Software_Veto

This test was introduced to remove cosmic-ray muons which
trigger the central detector. The instantaneous rate of the shield
veto causes a 13.5% dead time for the experiment, while at the same
time allowing some fraction of cosmic-ray muons to enter the central
detector. Approximately 50% of all the trackable triggers are in fact
cosmic rays which entered from outside the active veto shield. Other
running conditions of the active hardware veto have resulted in less
than 1% of the trackable triggers being cosmic rays. However, these
conditions have also resulted in an unacceptable dead time of up to 35%!

The cosmic-ray muon which passes through the six inches of liquid scintillator of the active shield produces a signal in the shield PMTs. These signals are recorded in the electronics and are used in the off-line software to veto the event. An algorithm is employed to find a cluster of shield PMTs that have fired. This cluster is defined as a group of visible signals which are in time coincidence and which are spatially correlated with one another. The time coincidence window for the PMTs is ±0.5 μs from the event trigger time. The positional proximity requirement is fulfilled if any two or more PMTs are within a distance of 1.2 m of each other. With this 1 μs time window and a spatial multiplicity of two or more, the cut eliminates roughly 90% of the cosmic-ray muons which triggered the central detector. Data were taken with a random trigger and were passed through this algorithm to determine how many events would be erroneously rejected because of chance coincidence due to PMT random singles noise. It was found that only 1.1% of the random triggered events are rejected. That is, 1.1% of electron events would be wrongly cut by this test. So the final data set of electrons is corrected by this amount.

5.2 Track Finder

A track finding algorithm\textsuperscript{48} was written for the central detector that searches the event for correlated hits in the scintillators and
PDTs. These hits must sit on or near an imaginary broad line called a "road". It also allows for misses due to the "dead" areas or inefficiencies of the devices along that "road". These misses are represented by a fractional number supplied by the user. For example, a track which is allowed to have 0.25 of the devices missing, means that only three out of four scintillators and/or three out of four PDTs along the track, are required to have an observable signal. As an example, the hits in Fig. 54 show an acceptable track because all of the devices have fired. Whereas the hits in Fig. 55 are not considered to constitute a track for the 0.25 misses parameter because two out of four PDTs are missing. If, however, the fraction of allowed misses were increased, say to 0.50, the event in Fig. 55 would now be considered a tracked event. Also note that a large value for the misses parameter, say of 0.75, would result in many erroneous tracks. This is especially true for electron tracks in which bremsstrahlung hits far away from the actual electron may be included in the track, thereby giving a longer track length. Values of 0.3 to 0.5 can be used without too many problems. For this analysis, a value of 0.5 was used.

Once a track is found, it is fit to a straight line. The physical coordinates of the endpoints of the track, the direction cosines, and the chi-squared fit of the track to the straight line are all calculated. The present analysis does not use the PDT drift time for position measurements. It uses only the wire position of the cell that is hit. The coordinate system for the detector is shown in Fig.
Figure 54

Graphics display of an acceptable track
where all of the devices are hit.
Figure 55

Graphics display of a track where not all the PDTs have fired.
Figure 56

Schematic diagram of the central detector and fiducial volume including a track's direction cosines.
The z axis is in the beam direction (west to east), the y axis is from bottom to top, and the x axis is from south to north. A plot of the z-axis direction cosine or \( \cos \theta \), and the "X" and "Y" PDT chi-square value of the fit are shown in Fig. 57, Fig. 58 and Fig. 59 respectively for electrons arising from stopped muon decay.

An electron generating Monte Carlo (EGS), with perfect detector efficiency, shows that only a small percentage (0.1%) of the tracks are not found. This is because those electrons radiate away so much energy, that only widely scattered scintillator hits are found in the central detector. In the actual detector, the primary contributions in reducing the track finding efficiency are due to PDT inefficiencies. Yet a Monte Carlo which includes the PDT inefficiencies has not been done and therefore no real number can be assigned to tracking efficiency at this time. A crude estimate can be done using the PDT efficiencies presented in Chapter 4. Note that the PDT efficiencies of Chapter 4 include the dead space in between the stacked PDT nine-banks within a plane. The average PDT nine-bank efficiency is 94.1% (see Fig. 26). If a track spans four scintillator planes, then only three "X" and three "Y" PDT planes are hit. The minimum non-track condition of an event occurs if two "X" or two "Y" PDTs are not hit. The probability for two out of three PDTs not firing when a track passes through the central detector is 1.64%.

A second estimate of the tracking inefficiency was done, which actually looked at those events which could not be tracked. It was found that 3.0% of the tracked events seemed to be scintillator and PDT
Figure 57

Histogram of the cosine-gamma values for electron tracks from stopped muon data.

Figure 58

Histogram of the chi-squared values of the fit to the electron tracks in the "X" projection.
Histogram of the chi-squared values of the fit to the electron tracks in the "y" projection.
hits lined up in a row, except that again two out of three "X" or "Y" PDTs did not fire. This latter value is used, and so for this analysis the tracking efficiency is assumed to be 97.0%.

5.3 Fiducial Volume Test

The fiducial volume cut performed on the data requires that a particle track have both its endpoints inside the fiducial volume of the central detector.

The physical dimensions of the central detector are 3.65 m high by 3.65 m wide by 7.16 m long, which gives a physical volume of 95.8 m$^3$. The fiducial volume surface is 20 cm from the outside of the central detector directed inward along the x and y directions, and 40 cm from the front and back along the z direction. So, the physical size of the fiducial volume is approximately 67.5 m$^3$ (Fig. 56).

The fiducial cut is used to provide a layer of protection against particles that may enter the central detector from the outside world. One type of protection simply involves the number of devices hit by an incoming particle, and the other type of protection involves the amount of material (in g/cm$^2$) traversed by that particle. The amount of material for the x-y-z fiducial cuts are different. The x and y fiducial cut involves about 20 cm of liquid scintillator, whereas the z fiducial cut involves 40 cm in real space, which amounts to only 9 cm of liquid scintillator. The small amount of material for the z fiducial cut is compensated by having many more devices which can sample the incoming particle. A track entering from the front would
have to hit three scintillator tanks, three "X" PDTs, and three "Y" PDTs in order to reach the fiducial volume surface. Yet, this track would pass through only 12 g/cm² of material. A track entering at 90° from the top or side of the central detector would hit only one scintillator tank but would travel through 17.3 g/cm² of material to reach the fiducial volume surface. And, of course, at some angle, say at 45°, the track would be sampled by only one scintillator tank, one "X" and one "Y" PDT plane, and traverse only 6 gm/cm² of material to reach the fiducial volume surface.

A quick test of the "holes" in the fiducial volume cut is provided by cosmic-ray muons. A trigger which provides a good set of muons is a logical AND of the "SHORT VETO" and "DET-OUT" signals, i.e. a muon which passed completely through the central detector and the active veto shield. This gives a rough estimate for the number of short electron type tracks which could slip into the fiducial volume undetected. The procedure is as follows. The data are passed through a program which tracks the muon and finds the physical coordinates of the track's endpoints. The angular distribution for cosθ of these tracks is shown in Fig. 60. Note that this histogram reflects the triggering acceptance of the detector as seen by the cutoff as cosθ approaches zero. It also reflects the cosine distribution of cosmic rays as seen by the histogram's falling off as cosθ approaches the value one. Normally both endpoints of the cosmic-ray muon should be outside the fiducial volume of the central detector, yet due to sampling inefficiencies, some of these tracks may have one endpoint
Figure 60

Histogram of the $\cos \gamma$ values for cosmic-ray muons passing through the central detector.

Figure 61

Histogram of the $\cos \gamma$ values for through-going cosmic-ray muons that were misidentified as being inside the central detector's fiducial volume.
inside and one endpoint outside the fiducial volume. A search of the
data is made for events that satisfy this type of condition, and their
\( \cos \theta \) plot is shown in Fig. 61. A division of the two histograms (Fig.
62) is made to take out the distribution of the muons in the initial
sample of Fig. 60. This shows the angular distribution of the fraction
of possible tracks that could have entered from outside the central
detector and were mistakenly identified as being inside the fiducial
volume. As can be seen in Fig. 62 the track angles greater than 74°
(\( \cos \theta = 0.4 \)) reveal the weakest point in the central detector’s ability
to provide a fiducial volume cut. About 90% of all fiducial “mistakes”
occur for tracks between 74° and 87°. However, a correction to these
results should be made. Short tracks trigger the detector at more
shallow angles than the “through” muon data collected here. So the
distribution of tracks in Fig. 62 should be multiplied by the \( \cos \theta \) plot
of stopped muon electrons in Fig. 57. The total number of short tracks
that are falsely identified as being inside the fiducial volume is then
shown in Fig. 63. The total fraction is 0.25% and the data are
corrected for this uncertainty in the fiducial volume cut by reducing
the number of final electrons by 0.25%.

5.4 Energy and Track Length Tests

The energy cuts performed on the data involve three specific
tests. The first cut tests the five energy values stated earlier in
Chapter 4. The second test involves a visible energy versus track
length comparison. And the third cut is a “dE/dx” measurement using
Figure 62

The fraction of through-going cosmic-ray muon fiducial "leakers" as a function of the muon $\cos \gamma$.

Figure 63

Histogram of the $\cos \gamma$ values for short electron track's fiducial that are considered "leakers".
the individual scintillator signals obtained from each tank that lies along the particle track.

5.4.1 Energy Cuts

There are five energies calculated for the particle per event, and the calculations are performed only on the data that lie within ±0.5 μs of the event trigger. The energies are

1. Visible Energy: uses only the scintillator PMT pulses for those scintillator tanks traversed by the track (using Eqn. 4.1).
2. Dead Energy: an estimate of energy lost by the tracked particle in the "dead" area between adjacent scintillator planes (using Eqn. 4.2).
3. Track Energy: the sum of the visible and dead energies. It is the entire energy lost by the particle along its track.
4. Associated Energy: essentially the logical complement of the track energy. It uses the visible scintillator PMT signals of all tanks in the central detector that are not hit by the track, and yet are in time coincidence with the track.
5. Total Energy: the sum of the visible, dead and associated energies.

The event can be eliminated if any one or more of these values is outside a given set of limits in the software. In the present analysis of the data, none of these energies are tested directly, yet they are looked at very closely during hand scanning to see if any of
them are out of the ordinary. For example, an event with a dead energy
or associated energy larger than the visible energy might indicate that
a fault occurred with the software while analyzing that event.

5.4.2 Visible Energy versus Track Length Cut

The physical length of the track in the central detector is
calculated and can be used in a track length cut. In Fig. 64 the track
length distribution for electrons from stopped muons shows that only
1.6% of the tracks are longer than 1.2 m.

The physical length of the track can also be employed in an
energy versus track length test. The scatter plot of visible energy
versus track length shown in Fig. 53, reveals an "electron" band
separated from the "proton" band. The cut that is used essentially
draws a "slice" through the "electron" band as shown in Fig. 65. Only
an event with a visible energy and track length within the "slice"
passes this test and is considered an "electron". The "slice" chosen in
Fig. 65 removes only 1.2% of the electrons from the stopped muon data
sample. The top line is purposely set high to allow some of the higher
energy background through the analysis. During the hand scan process,
these backgrounds can be examined to determine their characteristics
and also to determine the percentage that may fall squarely in the
"electron" band.

5.4.3 "dE/dx" Cut

The charged particle track as it traverses the central detector
gives a signal in each scintillator tank. The sum of these signals is
Figure 64

Histogram of the track length for electrons from stopped muon data.

Figure 65

Visible energy versus track length cut. Events within the band are kept on the analysis.
used to calculate the visible energy defined above. However, the individual scintillator tank signals also provide information that can be used to identify the particle that triggered the event. This analysis test is termed a "dE/dx" cut because it calculates a small amount of the track's energy (dE or the visible signal in that tank) along a small portion of the track's path (dx or the path length in the scintillator tank). The "dE/dx" values, from each scintillator tank that lies along the track can be compared to the "dE/dx" values obtained by the tanks from real electron data. This test is particularly useful since it can identify low energy "proton" type tracks, i.e. heavily ionizing particles. These "proton" type tracks can have a visible energy of 53 MeV or less, and yet may deposit a lot of their energy in only one or a few scintillator tanks.

The algorithm first corrects each PMT signal for the track angle, treating the track as if it were at normal incidence to the particular scintillator tank. Next the signal is normalized by the "muon-peak" values for that scintillator tanks' PMTs. This corrected and normalized pulse is then called the "dE/dx" value for that scintillator tank. A "dE/dx" value of one implies that the particle lost an amount of energy equal to a minimum ionizing cosmic-ray muon. A "dE/dx" value of two implies an energy loss in that scintillator tank, equal to a two times minimum ionizing cosmic-ray muon, etc.

The "dE/dx" values of all the tanks that lie along the track are then involved in a series of cuts. Since a track usually begins in the middle of one scintillator tank and ends in the middle of another
scintillator tank, most of the "dE/dx" values of the endpoint tanks will be less than one. However, the algorithm does not exclude the scintillator tanks which contain the endpoints of a track, because an endpoint scintillator tank may in fact have a large visible signal associated with the track. This is the case for a proton which loses a very large percentage of its energy near the end of its range. So, all tanks are used in two of the following three "dE/dx" cuts.

To calibrate this "dE/dx" test, a large set of electron data from stopped muons was used to calculate the "dE/dx" values for the scintillator tanks hit by the electron track. The "dE/dx" values for all tanks along the electron track are shown in Fig. 66. The plot reveals the low "dE/dx" values obtained from a partial entry of the track into the end scintillators. But, the "dE/dx" values from only the "middle" scintillator tanks, shown in Fig. 67, show a broad Landau type distribution with only a few zeroes (these are short tracks without a middle scintillator being hit). Shown in Fig. 68 is the average for the event of all scintillator tanks, while Fig. 69 shows the average of only the middle tanks hit. The cuts used are also shown in the figures. There are three limits used to keep an event:

1. All scintillator "dE/dx" values must be less than 2.5,
2. The average "dE/dx" value must be less than 1.4, and
3. The middle average "dE/dx" value must be less than 1.6.

These three cuts eliminate only 3.66% of the electrons obtained from
Figure 66
Histogram of the "dE/dx" values from all scintillator tanks for electron tracks from stopped muon data.

Figure 67
Histogram of the "dE/dx" values from all middle scintillator tanks from electron tracks from stopped muon data.
Figure 68

Histogram of the "dE/dx" average from all scintillator tanks for electron tracks from stopped muon data.

Figure 69

Histogram of the "dE/dx" average from all middle scintillator tanks for electron tracks from stopped muon data.
The stopped muons.

The "dE/dx" cut is not employed in the software analysis, but it is made during the hand scan process. This allows a firsthand observation of the events that have high "dE/dx" values. This is discussed in detail in Section 5.6.

5.5 Stopped_Muon_Cut

The aim of the stopped muon test is to see if the electron track that triggered the event came from a previously decayed, stopped muon. This type of event occurs quite frequently because, to reduce the dead time of the experiment to 13.5%, a relatively short "LONG VETO" value of 11 μs is used. Therefore, those muons which decayed more than 11 μs earlier can trigger the experiment.

This test first searches the data prior to the trigger to find a track in the central detector. If one is found, the coordinates of its endpoints are calculated. Then a proximity test is made to see if the x and y and z coordinates of the muon’s endpoints are each within a distance of 50 cm to one of the triggering electrons’ endpoints. If the tracks are near each other, a check is made to find a shield hit in time coincidence with the past muon track. When these conditions are met, the event is considered to be produced from a stopped muon.

If the above set of coincidences are not met, a second set of conditions is tested for, namely a "z-slice" cut. The z coordinate of the electrons’ tracks are extended by 50 cm in each direction. This defines the z-slice. The past muon track must have at least one
endpoint inside the z-slice region. Also the shield must have hits in time coincidence with the past muon track, and the z coordinate of the centroid of the shield hits must also be within the z-slice. A histogram of the time difference between the past muon track and the electron track for stopped muon events is shown in Fig. 70 and reveals the structure of the hardware veto.

These series of coincidences work very well in eliminating stopped muon events. A test with random triggers shows that this cut wrongly removes only 3.2% of the random events.

A note is needed concerning the irregularities or inefficiencies in tracking the muon and the electron. Sometimes the calculated endpoints for a real stopped muon event can be farther apart than 50 cm in any one of the three directions. This occurs for only a small fraction of the stopped muon events and can be visually eliminated when hand scanning the data.

5.6 Hand Scanning

The overall philosophy of the analysis is to make the previous cuts loose enough to allow more background to pass through the analysis so that it can be examined by hand. These are backgrounds which exist right around the region of interest, namely electron data below the energy of 53 MeV. It is necessary to find out how much of the background might extend into this "neutrino oscillation" region.

A time coincidence routine is employed to search for hits in the central detector and the active veto shield. This is very useful in
Figure 70

Histogram of the electron and muon time difference for events classified as a stopped muon trigger by the analysis.
eliminating the remaining stopped muon events. These events have only a few central detector devices hit in the past and could not be cut out of the analysis blindly, since no past track could be found.

During hand scanning all the information for energy, track length, and “dE/dx” values is displayed on the screen. This is used to make the “dE/dx” cuts described in Section 5.4. The “dE/dx” cuts were made without regard to the total energy or track lengths of the event.

The final results and classification of the data are discussed in the next chapter.

5.7 Summary

Table 3 shows a sample data run and a summary of the cuts used in the analysis. Also shown is the necessary corrections to the data. These corrections need to be made in order to obtain the true number of “electrons” events that exist on the data tapes and which are also in the detector’s entire physical volume.
Table 3
The analysis pass on the data tape NU008001.

<table>
<thead>
<tr>
<th>CUT</th>
<th>NUMBER OF EVENTS LEFT</th>
<th>PERCENTAGE OF EVENTS LEFT</th>
<th>EFFICIENCY$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start</td>
<td>11,807</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Shield Veto</td>
<td>6,471</td>
<td>54.8</td>
<td>0.989 (±0.031)</td>
</tr>
<tr>
<td>Track Found</td>
<td>3,833</td>
<td>32.5</td>
<td>0.970 (±0.024)</td>
</tr>
<tr>
<td>Fiducial Volume</td>
<td>1,771</td>
<td>15.0</td>
<td>0.777 (±0.011)</td>
</tr>
<tr>
<td>Muon Peak</td>
<td>1,429</td>
<td>12.1</td>
<td>0.798 (±0.010)</td>
</tr>
<tr>
<td>Range - Energy</td>
<td>716</td>
<td>6.06</td>
<td>0.988 (±0.021)</td>
</tr>
<tr>
<td>Stopped Muon</td>
<td>93</td>
<td>0.79</td>
<td>0.968 (±0.040)</td>
</tr>
</tbody>
</table>

TOTAL = 0.569 (±0.036)

$^a$ The efficiency is defined as the fraction of good electron-like events that are not randomly removed by the cut.
Chapter 6

Results of the Engineering Run

The results and indications of the data collected during the 1986 engineering run are discussed and further analyzed in this chapter. It is shown that the neutron induced, beam associated background of the electron-like signal of inverse beta decay can be reasonably eliminated. There is however a large loss in software efficiency and a large error on the result. The result, after subtraction of the cosmic-ray background, is equal to 0.04 (±0.6) electron-like events per LAMPF-day. The analysis described in this chapter reveals that if the neutron background is removed by further shielding of the LAMPF beam stop, E645 should be able to reach its proposed neutrino oscillation sensitivity.

6.1 General Data Run Information

The E645 detector was used to take data during LAMPF cycle 47 in the fall of 1986. The data run involved a small number of tests and employed a number of different running conditions. But the bulk of the data was collected with a "4-AND" central detector trigger. This analysis is concerned only with the "4-AND" data.

The real running time, taken from the first to last data tape, was 28 days, with only 18.6 days of collecting "4-AND" data. But the total live time during the beam gate, in which the detector trigger is
enabled to take data was only 11.38 LAMPF-days. This implies an overall live time factor of 0.612. There were three causes for this difference between the expected live time of 18.6 LAMPF-days and the measured live time of 11.38 LAMPF-days.

1. LAMPF down time, measured from the LAMPF control room records. It shows that the beam live time was 0.853. Note that this includes scheduled down time for maintenance days.

2. The E645 clipped beam gate which is 700 μs long and therefore gives an experimental 5.6% duty cycle. This is a factor of 0.862 with respect to the LAMPF 6.5% duty cycle.

3. The E645 dead time, due to the active veto shield’s "LONG VETO" length and the experiment’s CAMAC readout time after a trigger has occurred. The value of this dead time is measured and stored on the magnetic data tapes. The experiments fractional live time as measured with the "6ACM-1" beam counter is 0.842.

The product of these three factors is equal to 0.619, explaining most of the experiment’s dead time. Note here that a LAMPF-day is taken to be 5616 seconds or a 6.5% duty cycle.

The primary beam related quantity used in the experiment is the integrated current produced by the LAMPF proton beam. This charge determines the number of neutrinos that are emitted from the beam stop. The LAMPF "6ACM-1" counter was used and provided a measurement of 845.7 Coulombs on target for the 11.38 LAMPF-days. If E645 had not used the clipped beam gate, this number would have been 3.5% higher.
Along with the beam gated data, another gate is used which enables the detector for data taking while the beam is off. This is called the cosmic-ray gate and measured a total of 31.6 LAMPF-days worth of live time. The ratio of these two gate times was used to remove the cosmic-ray induced triggers that occurred while the beam gate was on. This ratio is 0.3606. As an example, the hand scan stopped muon results gave 359 stopped muon triggers in the beam gate and 922 triggers in the cosmic-ray gate. Subtracting the cosmic-ray gated number times 0.3606, from the beam gate number, gives 26.5 (±21.8) beam excess stopped muons. This number is consistent with zero, i.e. there should be no beam excess triggers due to cosmic-ray stopped muon electrons.

During the run, 331,393 triggers were collected. The average data taking trigger rate was equal to 0.206 Hz. The instantaneous trigger rate was 1.65 Hz in the beam gate and 1.20 Hz in the cosmic-ray gate. This beam excess trigger rate of 0.45 Hz (±0.01 Hz) is just one indication that E645 suffers from beam related backgrounds.

6.2 Hand Scan Classified Events

The 34 "4-AND" data tapes (331,000 triggers), after being passed through the analysis program described in Chapter 5, were reduced to just 2320 events to hand scan. Events were categorized into:

1. "Clean" electron-like events with a total energy less than 70 MeV (97 events). These events have lower "dE/dx" values, and there
are up to 55 µs prior to the trigger, no "past" data hits near the triggering track.

2. High energy electron-like events with a total energy greater than or equal to 70 MeV (248 events). These high energy events are typified by a long track accompanied by a large amount of bremsstrahlung energy.

3. High "dE/dx" events with a "dE/dx" value greater than the cuts described in Chapter 5 (305 events). These events were removed without regard to their total energy. Note that most of these events passed the analysis cuts because of the intentional high range-energy cut described in Section 5.4.

4. Stopped muon electrons with very few muon hits in the central detector (1282 events). The identification of these events was accomplished by searching for any time coincidence signal within 1 µs between the central detector's scintillators or PDTs and the active veto shield's PMTs.

Two other less important classes were observed:

5. "Dirty" electron-like events with a total energy of less than 70 MeV (18 events). These events have some scintillator or PDT hits which occurred in the past, near the triggering track.

6. "Vee" events that look like two separated tracks which seem to connect at a vertex (26 events).
From the clean "electron-like" data set, a further energy cut was made. This cut gave 47 events with a total energy less than or equal to 53 MeV, and are defined from now on as the low energy "electron-like" data set.

The rates for the "4-AND" trigger and detection of these types of events are displayed in Table 4. Shown are the raw numbers obtained from the analysis pass of Chapter 5. Also shown are the corrected rates which provide the true number of events on the magnetic tapes that occurred within the entire physical volume of the central detector. The corrected events are determined from the software efficiency of 0.57 (±0.04) tabulated in Chapter 5. The 'second analysis' column is described in Section 6.3.

As can be seen in Table 4 there exists a large number of "electron" like backgrounds that hover very near the neutrino oscillation signal region, i.e. low energy electrons that would be produced from an inverse beta decay reaction. In fact, if all the events from the first three classifications are plotted on a single histogram shown in Fig. 71, a continuous distribution is seen. A scatter plot of visible energy versus track length also shows the overlap of the three types of events (Fig. 72). The high energy electrons with an energy greater than 53 MeV and the high "dE/dx" events are clearly not due to inverse beta decay reactions. However, their presence suggests that the events with an energy lower than 53 MeV may simply be the tail of these two types of numerous backgrounds.
Table 4

Classified types of data and their "4-AND" rates per LAMPF-day.

<table>
<thead>
<tr>
<th>Hand Scan Classification</th>
<th>Cosmic-Ray Gate &quot;4-AND&quot; Rate (Per LAMPF-Day)</th>
<th>Beam Excess &quot;4-AND&quot; Rate (Per LAMPF-Day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Raw Rate(^{a)})</td>
<td>Corrected(^{b)})</td>
</tr>
<tr>
<td>&quot;Electron&quot; (Energy&lt;53 MeV)</td>
<td>0.70 (±0.15)</td>
<td>1.23 (±0.28)</td>
</tr>
<tr>
<td>&quot;Electron&quot; (Energy&lt;70 MeV)</td>
<td>1.39 (±0.21)</td>
<td>2.44 (±0.40)</td>
</tr>
<tr>
<td>&quot;Electron&quot; (Energy&gt;70 MeV)</td>
<td>3.29 (±0.32)</td>
<td>5.78 (±0.67)</td>
</tr>
<tr>
<td>High &quot;dE/dx&quot; Events</td>
<td>2.90 (±0.31)</td>
<td>5.10 (±0.65)</td>
</tr>
</tbody>
</table>

\(^{a)}\) Raw rates are obtained after the first pass analysis and hand scan.
\(^{b)}\) The corrected rates account for software efficiency and are a measure of the true number of events on the 34 data tapes.
\(^{c)}\) The second analysis cut for cosmic-ray gated data employs only a 15 μs active veto shield time cut.
\(^{d)}\) The second analysis cut for beam excess events employs only the PDT "dE/dx" chi-squared cut.
Histogram of the total energy for the low energy "electron", high energy electron, and high "dE/dx" data sets.

Plot of visible energy versus track length for the low energy "electron", high energy electron, and high "dE/dx" data sets.
One indication that these low energy tracks are not due to neutrino interactions is the non-uniform spatial distribution of the events. Neutrinos would interact fairly uniformly inside the central detector except for the small inverse distance-squared effect, which would amount to a 30% reduction of events in going from the front to the back of the central detector. The z-distribution of the two endpoints of each low energy track is plotted for the cosmic-ray gated events in Fig. 73, and for the beam excess events in Fig. 74. A large number of the beam excess events in Fig. 74, begin and end in the front of the central detector; the end closest to the beam stop. The opposite is true for the cosmic-ray gated events of Fig. 73.

6.3 Further Analysis

In this section, it is shown very clearly that the low energy "electrons" detected by the apparatus and previous analysis, are in fact not electron-like at all. This is done by a very close comparison between the low energy "electron" data set and true electrons obtained from stopped muons. The stopped muon data set is used because it provides the best source of real electrons whose energies lie in the same range as the inverse beta decay electrons.

To this point in the analysis the software cuts have had a reasonable effect on the experiment's efficiency for finding electrons in the central detector. The detection efficiency for inverse beta reactions due to the cuts is 0.569. This will improve to approximately 0.677 in future runs since the central detector is being made more
Histogram of the z position of track endpoints for the cosmic-ray gated low energy "electron" data set.

Figure 73

Histogram of the z position of track endpoints for the beam excess low energy "electron" data set.

Figure 74
efficient. The "second analysis" cuts that are made on the remaining low energy "electrons" have a severe effect on this software efficiency. However, it is necessary to make these further cuts in order to see if there is in fact a real electron background. This information obtained here is particularly useful in planning for the future run.

6.3.1 Cosmic-Ray Background Cut

From the hand scan results there are 22 low energy events in the cosmic-ray gate. To find out if these events are somehow associated with cosmic-ray stopped muons, the active veto shield digitizer history is used to see if there were shield hits prior to the trigger. Plotted in Fig. 75 is the time difference between the triggering track and the most recent shield hit for identified stopped muon triggers taken from the hand scan data. Note the peak at 11 μs, which is the length of the hardware "LONG VETO". This peak is characteristic of stopped muon induced triggers. The same plot is made for the low energy data set in the cosmic-ray gate shown in Fig. 76, and it too reveals an 11 μs peak.

A cut is made on the data, in which all events are rejected if a shield hit occurred 15 μs before the trigger. This eliminates nearly 85% (±4%) of real stopped muon triggers. At the same time it erroneously cuts out only 16.5% (±1.2%) events that have random shield coincidence as shown in Fig. 77. After this cut is made, and re-corrected to account for the random removal of non-stopped muon
Figure 75

Histogram of the time difference between the trigger and past shield hits for the cosmic-ray gated stopped muon electron data set.

Figure 76

Histogram of the time difference between the trigger and past shield hits for the cosmic-ray gated low energy "electron" data set.
Figure 77

Histogram of the time difference between the trigger and past shield hits for cosmic-ray gated randomly triggered events.
events, the final cosmic-ray background rate drops from 1.23 (±0.28) events per LAMPF-day to 0.47 (±0.18) events per LAMPF-day. The software efficiency also drops from 0.569 to 0.475.

6.3.2 Beam Excess Background Cut

From the hand scan results, there are 25 low energy events in the beam gate. A cosmic ray subtraction to this data is performed to get 17.1 (±5.3) events as the beam excess result for the 11.4 LAMPF-days.

Up to this point, only the scintillator information has been used to get the earlier beam excess result of 2.6 (±0.8) "4-AND" triggerable events per LAMPF-day. Now in the second analysis pass, the PDT pulse areas are used to try to identify the particles that make up this low energy data set. As stated in Section 4.4, the "X" and "Y" PDT nine-bank "muon-peaks" are stored and used in a chi-squared fit for each event:

$$
\chi^2 = \frac{1}{N} \sum \left( \frac{p_i - s_i}{\sigma_i} \right)^2
$$

[6.1]

where $s_i$ = the pulse area from the PDTs

$p_i$ = the peak of the pulse area distribution for a real electron data set

$s_i$ = standard deviation in the electron pulse area distribution

$N$ = number of "X" and "Y" planes hit by the track.

These PDT "dE/dx" chi-squared values for real stopped muon electrons obtained from the beam gated hand scan results are plotted in Fig. 78.
Figure 78

Histogram of "x" and "y" PDT "dE/dx" chi-squared values for the beam gated stopped muon electron data set.

Figure 79

Histogram of "x" and "y" PDT "dE/dx" chi-squared values for the beam excess low energy "electron" data set.
The PDT "dE/dx" chi-squared values for the beam excess events are plotted in Fig. 79. A cut in the chi-squared value greater than 3.0 eliminates 49.3% (±4.5%) of real electrons whereas it cuts 99% (±34%) of the beam excess events. When the cosmic-ray events are subtracted from the beam gated data, the beam excess rate is reduced to 0.04 (±0.6) events per LAMPF-day.

This PDT "dE/dx" chi-squared cut, when made on the high "dE/dx" data set, also removes almost all of the events (Fig. 80). The high "dE/dx" beam excess rate drops from 27.6 to 2.9 events per LAMPF-day.

In performing this cut the software efficiency drops from 0.569 to 0.288 (±0.032).

6.3.3 Electron Bremsstrahlung

As further proof that the 17.1 beam excess events are not electron-like particles, another quantity obtained from the analysis program is employed. This number is the cosine of the opening angle \( \cos \theta_{e-\gamma} \) between the particle track direction and the location of associated hits in the central detector.

For real electrons these associated hits are bremsstrahlung which of course are emitted parallel to the direction of the electron track. The cosine of this opening angle is plotted in Fig. 81 for beam gated stopped muons identified during the hand scan. It shows a clear peak at \( \cos \theta_{e-\gamma} \) equal to 1. The two peaks, one at +1 and one at -1, are due to the ambiguity in the track direction, i.e. the electron could be travelling from the front to the back or from the back to the front of
Figure 80

Histogram of "X" and "Y" PDT "dE/dx" chi-squared values for the beam excess high "dE/dx" data set.
Figure 81

Histogram of $\cos\theta_{e-\gamma}$ values for the beam gated stopped muon electron data set.

Figure 82

Histogram of $\cos\theta_{e-\gamma}$ values for the beam excess low energy electron data set.
the central detector. Shown in Fig. 82 is the \( \cos \theta_{e-\gamma} \) quantity for the beam excess results, and it is noticably flat. In Fig. 83 the \( \cos \theta_{e-\gamma} \) values are plotted for the cosmic-ray gated, low energy events. It shows a clustering near \( \cos \theta_{e-\gamma} \) equal to \( \pm 1 \), which is consisent with the earlier statement that these are electrons emanating from stopped muons.

If the \( \cos \theta_{e-\gamma} \) values are plotted for the beam excess high \( "dE/dx" \) events, it also reveals a flat distribution as shown in Fig. 84.

6.3.4 Discussion

This crude and preliminary analysis seems to show that the low energy "electron" events, when compared to stopped muon electrons, are not electrons at all. Furthermore, these low energy events merely appear to be the tail of the high "dE/dx" hand scan classified events. It is suggested here that these events are in fact pathologically detected protons or charged pions. This is discussed in the next section.

However, two points should be made. First, the overall software efficiency is only 0.241 (\( \pm 0.028 \)) after the two cuts described in Sections 6.3.1 and 6.3.2 are implemented. This low efficiency is unacceptable because it severely reduces the oscillation sensitivity of E645. All attempts should be made to try to eliminate the neutron background and the cosmic-ray muon induced events and therefore eliminate the need for these two extra cuts.
Figure 83

Histogram of \( \cos \theta_{e-\gamma} \) values for the cosmic-ray
gated low energy "electron" data set.

Figure 84

Histogram of \( \cos \theta_{e-\gamma} \) values for the beam excess high "dE/dx" data set.
Secondly, the two cuts above affect only one of the two gated data sets; the cosmic-ray gated, low energy events or the beam excess, low energy events. That is, the active veto shield time cut eliminates most of the cosmic-ray gated events, while only randomly affecting the beam excess events. Likewise the PDT chi-squared cut removes most of the beam excess data while only randomly removing the cosmic-ray events. This illustrates the fundamental difference between the two gated data sets, namely the beam excess events are being produced from a very different source and in a very different way than the cosmic-ray gated events. As stated earlier, the belief is that the beam excess events are protons or charged pions produced from beam associated neutrons, while the cosmic-ray gated events are electrons, probably coming from undetected stopped muons.

6.4 Beam Excess Particle Production

Two types of particles, each produced from beam neutrons, are discussed in terms of their ability to mimic a true inverse beta decay electron.

6.4.1 Proton Triggers

The particles that comprise the "electron-like" data set have an energy between 20 and 53 MeV and a track length between 40 and 100 centimeters. At first blush this would seem to rule out protons which would have to have at least 120 MeV and travel at normal incidence to the scintillator tanks in order to satisfy a "4-AND" trigger.
One possible proton trigger configuration may be a short proton track coupled with associated hits. For example, a "3-AND" proton track with an extra hit in an adjacent plane would be enough to trigger the "4-AND" pattern. In fact, one half of the beam excess tracks in the low energy data set have only three scintillator tanks, probably caused by a short "3-AND" track. In addition, there are a lot of extra hits in the central detector which accompany knock-on protons observed in the data. These protons, defined as the larger energy tracks as seen in the proton band of Fig. 53, were passed through the analysis program. It was found that on the average there are 1.9 associated hits per event. For comparison, there are only 0.14 associated hits per event for a beam gated random trigger.

This associated activity is confirmed by a High Energy Transport Code (HETC)\textsuperscript{49} Monte Carlo which traces neutrons with an energy spectrum of those coming from the LAMPF beam stop. Each incident neutron produces 2.4 protons within a simulated central detector. The proton energy distribution is peaked towards low energies; only 0.93 protons are produced with an energy greater than 100 MeV. At the same time there are also 3.2 neutrons produced per incident beam neutron. Their energy distribution gave 1.0 neutrons produced between one and ten MeV, which is the most efficient energy region for neutrons to be detected in liquid scintillator.

So, in summary, there is a lot of activity occurring around any knock-on "3-AND" triggerable proton. However, here again the minimum energy needed for a proton to traverse the necessary "3-AND" material
is 90 MeV. This would again seem to rule out a "4-AND" trigger consisting of a "3-AND" proton track coupled with an extra associated hit.

The only possible proton trigger to remain is a proton track which clips the corner of one or more middle scintillator tanks. This implies that a very large discrepancy will exist between the true energy of the particle and the visible energy deposited in the liquid scintillator. For example, a proton track which is created in the last centimeter of the first tank, clips the corners of the next two tanks, and then stops in the first millimeter of the last tank, could register a visible signal of, say 35 MeV. But the true energy needed to traverse that distance would be about 80 to 90 MeV.

Under these circumstances, only the PDTs would view the full proton track and would thereby give large "dE/dx" values for that event. This is exactly what is seen for the beam excess events; minimum ionizing "dE/dx" values in the scintillator, but largish "dE/dx" values in the PDTs.

The only effect limiting the number of these proton corner clipping events is the solid angle acceptance of the dead space in between the central detector's scintillator tanks. The probability that a proton would start in a centimeter and stop in a millimeter of the end tanks and clip the corners of the two middle tanks, must be very small. A detailed proton Monte Carlo, simulating the rounded scintillator tanks, is the only feasible way to see if this corner clipping scenario in fact accounts for all of the low energy, beam
excess events.

6.4.2 Pion Triggers

One other particle type that must be considered is the charged pion. Charged pions can produce large pulse heights in the PDTs and near minimum ionizing "dE/dx" values in the scintillator tanks. Also, pions are not restricted by the corner clipping effect in order to be erroneously identified as a low energy "electron" event. The energy needed by a normally incident pion to satisfy the minimum "4-AND" trigger requirement is 42 MeV. Also, a pion needs at least 32 MeV of energy to trigger a "3-AND" pattern.

These pions' visible energies as measured in the liquid scintillator are underestimated from their true energies due to a systematic effect known as Birks' Law. This law relates the primary number of photons produced by a traversing particle in liquid scintillator to its ionization energy loss. The equation governing this photon yield is

\[
\frac{dN(Y)}{dx} = \frac{A}{(1 + B \frac{dE}{dx})} \cdot \frac{dE}{dx}
\]

where \(dN(Y)/dx\) is the number of scintillation photons produced per unit distance, \(dE/dx\) is the ionization energy lost by a particle in the scintillator, \(B\) is a constant equal to \(8.8 \times 10^{-3} \text{ g/cm}^2\text{-MeV}\) for liquid scintillator, and \(A\) is a proportionality constant.
As an average example, a 40 MeV pion will produce 29% less light in the scintillator tanks than a 40 MeV electron. So, if these 20 to 53 MeV particles are in fact pions, their true energy would be 30 to 75 MeV, and therefore they would have enough energy to easily produce a "3-AND" or a "4-AND" trigger.

To see the largest effect of Birks' Law on the photon yield as a function of a particle's energy loss, consider pions at the end of their range. A 16 MeV pion would stop in exactly three centimeters of liquid scintillator, thereby losing almost three times the energy that a 400 MeV muon would deposit. Recall that these through-going muons are used to calculate the "muon-peaks" which calibrate the scintillator PMTs. However due to Birks' law, the number of primary photons produced by the 16 MeV pion is about 50% less than that of a minimum ionizing track! This results in essentially an electron-like visible signal for the last part of a pion's track. This is why it is extremely difficult to identify pions using only the scintillator signals. The PDTs are not subject to this reduced signal effect, because they collect the primary ionization electrons produced by the energy loss of the traversing particle.

Secondly, the central detector is nicely set up to identify protons. As the proton slows down, the last several scintillator tanks view a large "dE/dx" value due to the increasing energy loss of the proton. But for 50 MeV pions, the energy loss is very small and until the pion energy is reduced to between 15 and 20 MeV, the scintillators' "dE/dx" values nearly equals the "dE/dx" values of electrons. So,
towards the end of its range, the 20 MeV pion can exit one scintillator tank and stop in the next adjacent tank and produce a visible signal similar to electrons. However, the last "X" and "Y" PDTs along the track observe a 10 MeV pion, which in P-10 gas deposits four to five times the energy compared to a 400 MeV muon.

This crude and general argument illustrates the problems that could occur in trying to identify pions in the central detector and the necessity of using the PDTs in the particle identification process.

The HETC Monte Carlo gives a very large beam neutron induced, pion production rate, in relation to the proton production rate. This Monte Carlo was run in a very simple fashion and may only be valid to within a factor of two or three. However, the general theme suggests as many as 600 $\pi^0$, 480 $\pi^-$, and 150 $\pi^+$ particles are produced per LAMPF-day.

6.4.3 Charged Pion Production

The charged pion production rate is quoted by the Monte Carlo as the total number of pions created inside the entire volume of the central detector. The number of pions which can trigger the "4-AND" requirement is not known at this time. A thorough trigger simulation using the Kent State Neutron Efficiency Monte Carlo was performed for protons created by incident beam neutrons. It is shown that only 1% of the neutrons between 200 and 800 MeV would knock on a proton with enough energy to satisfy the "4-AND" trigger. If that number is (perhaps erroneously) applied to pions, it predicts 21 $\pi^-$ and 7 $\pi^+$.
triggered events per LAMPF-day. If all of the high "dE/dx" events found in the hand scan are considered to be charged pions, then the rates closely match those of the HETC results. From Table 4 it is seen that there are 27.6 high "dE/dx" events per LAMPF-day observed in the data.

A π⁺ particle stops and decays into a muon, and the muon decays into an electron. While hand scanning these high "dE/dx" events, only two out of approximately 80 events were found to have a decayed track in the "future", that is, about two to three microseconds after the pion trigger. This is much smaller than expected, because if these high "dE/dx" events are charged pions, about one-quarter of them should be π⁺'s.

Other data sets might have to be considered when looking for π⁺ events. For example, some or all of the 0.90 (±0.50) beam excess "dirty" events per LAMPF-day might be π⁺ particles. Recall that a "dirty" event has some hits near the trigger track, but these hits occurred before the trigger. Likewise, the 1.28 (±0.60) beam excess "vee" events per LAMPF-day, which are made up of two tracks in time coincidence that connect at a vertex, may also be π⁺ events.

The π⁻ particles do not decay in the presence of matter. They stop, are captured by an atom, and then absorbed by the carbon nucleus in hundreds of picoseconds. This absorption time is very small compared to the 27 nanosecond mean lifetime of the π⁻. The π⁻ capture occurs essentially on carbon and results in the emission of protons and/or neutrons from the nucleus. About 70% of the captures result in one or more protons being emitted from the excited nucleus. The
other 30% of the $\pi^-$ captures create up to three neutrons which are emitted with an energy greater than 2.5 MeV. Only 1.2% of the captures release photons with the nuclear breakup.

Captures of $\pi^-$ also occur on free protons in the CH$_2$ molecule of the liquid scintillator, about 1.3% of the time. This results in a 130 MeV photon and a 10 MeV neutron being emitted from the $\pi^-p$ reaction. Also, these captures result in a $\pi^0$ being produced which decays in flight into two photons. Accompanying the $\pi^0$ is a neutron with a kinetic energy of less than 1 MeV.

The important result in the $\pi^-$ capture reactions, on carbon or protons, is the emission of protons, neutrons, or photons. These extra particles could end up causing associated hits in the central detector. In fact the beam excess high "dE/dx" data set, classified from the hand scanning, have on the average 3.9 associated hits in time with the triggering track. This is the same for the beam excess low energy "electron-like" events, which have 3.9 associated hits per event. This is to be compared with 2.3 associated hits for stopped muon electrons, 1.9 associated hits for proton tracks, and 0.14 associated hits for beam gated random triggers. This extra activity in the detector for the high "dE/dx" and low energy tracks may be explained if the events consist mostly of $\pi^-$ particles. The mechanism for this factor of two increase in the associated hits for the low energy events compared with other data sets can be explained as follows. Recall from the HETC results that the incident neutron can produce about 2.5 protons and about 3.5 neutrons and create a $\pi^-$ at the
same time. The \( \pi^- \) after being captured results in about three more
neutrons or one or two more photons. All of this extra activity before
and after the \( \pi^- \) triggers may result in the high number of associated
hits seen in the central detector.

So, in summary it appears reasonable to consider the beam neutron
induced \( \pi^- \) particles along with proton corner clippers as comprising
most if not all of the low energy "electron-like" data set.

6.4.4 Neutral Pion Production

The \( \pi^0 \)'s decay into two photons. An EGS Monte Carlo\(^{56}\) run with 70
MeV photons generated randomly through the central detector, showed
that 5.7\% of these photons would produce a 20 to 53 MeV electron that
is capable of satisfying the "4-AND" trigger condition. This results
in about 34 \( \pi^0 \) induced low energy electrons per LAMPF-day. Besides the
fact that the low energy beam excess events are not electrons, the rate
from Table 4 for the low energy data set is only 2.6 events per
LAMPF-day; a factor 13 too small compared with the EGS Monte Carlo. The
70 MeV EGS Monte Carlo also predicts the rate of high energy electrons
of 54 MeV or greater to be 81 events per LAMPF-day. The data show that
the number of electrons observed with an energy greater than or equal
to 54 MeV is 20 per LAMPF-day; a factor of 4 too small compared with
the EGS result.

It is difficult to imagine any mechanism except \( \pi^0 \) decay in
flight which could produce these high energy electron events.
Therefore this discrepancy leads one to question the simplistic model
of the $\pi^0$ decaying at rest.

The HETC Monte Carlo shows that the $\pi^0$ energy peaks at around 30 to 40 MeV. This non-zero momentum for the $\pi^0$ produces a Doppler shift for the decayed photons. Rather than an isotropic distribution of photons as occurs in the $\pi^0$ center of mass system, more photons are now produced in the laboratory system inside the forward cone along the initial $\pi^0$ direction. This results in a boosted energy of greater than 70 MeV for more than half of the photons. A smaller fraction is emitted in the backward cone but with a reduced energy of 30 to 40 MeV. The remainder is produced within a volume that is perpendicular to the $\pi^0$ direction.

At this point a directionality to the neutral pions must be introduced. The $\pi^0$s are created with a velocity essentially within zero to twenty degrees of the incident neutron direction. Also, the neutron direction is taken to be generally along the beam direction, i.e. from the front to the back of the central detector. Therefore, those photons emitted in the perpendicular cone can only produce Compton electrons or an electron-positron pair also perpendicular to the $\pi^0$ direction. These possible electron tracks are prevented from triggering the experiment due to the layered geometry of the detector. The higher energy photons emitted in the forward cone produce mainly higher energy electrons which are greater than 53 MeV. The lower energy photons emitted in the backward cone can produce lower energy electrons from 33 to 45 MeV but at a smaller rate than the 70 MeV photon Monte Carlo suggested.
To sort out exactly what is going on, all of these considerations must be taken into account in order to understand why the large π° production rate does not produce electrons in the beam excess, low energy data set. A more sophisticated photon Monte Carlo needs to be performed with two photons being produced from each π°. Also the π°s should have an energy distribution given by the HETC results and with a possible "directionality" as discussed above. And finally, the Monte Carlo should include π° production around the inside of the active veto shield. This would then give rise to extra photons entering from outside the central detector.

6.4.5 Summary

In summary, two possible particles were considered in order to explain the beam excess low energy data set.

First was the proton. If they clipped the corners of the scintillator tanks, they would be misidentified as having a very small visible energy. The PDT "dE/dx" values would then be the only handle in identifying protons. On the one hand, there may be a small probability for depositing a small amount of visible energy by partial entry in the end scintillator tanks and clipping the corners of the remaining middle scintillator tanks. On the other hand, there are a lot of beam excess protons being produced; approximately 1300 protons per LAMPF-day.

Next, charged pions were discussed. The main reason to consider a π⁺ or a π⁻ particle is that there exists such a large number of high
energy electrons; almost 20 beam excess high energy electrons per LAMPF-day. The only way to produce high energy electrons is via \( \pi^0 \) decay in flight. And where there are \( \pi^0 \) particles being produced, one must also assume a similar rate for the creation of \( \pi^- \) and \( \pi^+ \) particles.

Pions are difficult to distinguish from electrons when using the scintillator PMT signals alone. Employing the PDT signals may help in identifying charged pions in the central detector.

Charged negative pions do not decay and are not bound by the corner clipping scenario in order to mimic electron-like events. However, there may not be enough \( \pi^+ \) events observed in the detector through the \( \mu-e \) decay chain to justify a large \( \pi^- \) production rate.

And finally, it is not completely understood why the one truly dangerous background of \( \pi^0 \) decay did not induce a lot of low energy electron triggers for the 11.4 LAMPF-day engineering run.

6.5 Likelihood Fit

The analysis, once completed, provides a beam excess result. In this case the value of 0.04 (±0.6) events per LAMPF-day is consistent with zero events with an uncertainty of ±0.60 events per LAMPF-day. The next step is to use this null result to rule out the values of \( \sin^2 2\theta \) and \( \delta m^2 \) which should have given a positive signal for neutrino oscillation. In order to obtain the best statistical limits on this oscillation sensitivity, a more sophisticated approach than just quoting a number needs to be employed. This section briefly outlines
the likelihood fit used to obtain the sensitivity curves for the 11.4 LAMPF-day run.

The energy reconstruction of the central detector allows the final data to be split up into three energy bins. This increases the sensitivity of the experiment, because there are effectively three L/E values from which to test the oscillation process. The cosmic-ray gated data is then subtracted from the beam gated data, to obtain the number of beam excess events for each energy bin. The uncertainties in these numbers for each bin are also used in the likelihood fit.

On the other side of the process is the numerical calculation of the number of $\bar{\nu}_e p$ inverse beta decay events that would be detected if there were maximum oscillations. The neutrino spectrum, the average inverse beta decay cross section, and the detector response are all calculated, again for each energy bin. These quantities, in each energy bin, give the maximum number of electrons that could trigger the E645 central detector. A simultaneous comparison between the theoretical number and the experimentally observed number of beam excess, low energy electrons for all three energy bins is then performed for a selected value of $\sin^2 2\theta$ and $\delta m^2$. After the entire parameter space is mapped out with these likelihood values, a 90% confidence limit contour is found. This represents the experiment's sensitivity curve to the neutrino oscillation process.
6.5.1 Input Parameters

A brief outline of the necessary input parameters to the likelihood fit are described in this section.

1. The number of neutrinos generated at the beam stop is calculated using the proton current monitor result of 845.7 Coulombs on target. A neutrino per proton ratio of 0.079 results in $4.17 \times 10^{20}$ neutrinos produced for the 11.4 LAMPF-day run. Note that due to uncertainties in the water degrader neutrino production rate, and the changing configuration of the isotope production stringers, this number may contain as much as a 12% systematic uncertainty\(^5\).

2. The number of free protons in the central detector is calculated to be $1.60 \times 10^{30}$. The breakdown is as follows:

   A) liquid scintillator: $1.23 \times 10^{30}$ protons
   B) Lucite tanks: $0.205 \times 10^{30}$ protons
   C) PDT cardboard: $0.157 \times 10^{30}$ protons

   A systematic uncertainty of 5% is assumed for the total number of protons in the central detector.

3. The three energy bins are defined as follows:

   A) Bin 1: 20 MeV to 29 MeV.
   B) Bin 2: 30 MeV to 39 MeV.
4. The fraction of the beam neutrinos in each energy bin, taken from the $\nu_\mu$ Michel spectrum (Fig. 4) is:

A) Bin 1: 0.171
B) Bin 2: 0.276
C) Bin 3: 0.470
D) 0 MeV to 19 MeV: 0.083

5. The average cross section for each energy bin is (in cm$^2$):

A) Bin 1: 0.538x10$^{-40}$
B) Bin 2: 0.990x10$^{-40}$
C) Bin 3: 1.65x10$^{-40}$

Note that this cross section is a theoretically calculated number, and has not been measured at these low energies. It is therefore assumed to have as much as a 20% systematic uncertainty for each energy bin.

6. The average distance from the beam stop to the central detector is 2600 cm. This implies a range of L/E values (in m/MeV) taken at the central energy of each bin:

A) Bin 1: 1.04
B) Bin 2: 0.743
C) Bin 3: 0.565
7. The number and uncertainty in the number of beam excess events are taken over the entire run and calculated for each bin. However, there were a very small number of events left after the PDT "dE/dx" chi-squared cut; three events in the beam gate and eight events in the cosmic-ray gate. All three beam gated events fell in the first energy bin. After the software correction is made, the number of beam excess events in each bin is:

A) Bin 1: 5.42 (±6.56)
B) Bin 2: -2.50 (±1.47)
C) Bin 3: -1.25 (±1.26)

Due to the limited statistics of the short run and the inefficient analysis, negative numbers result in the last two energy bins. The way the likelihood program is set up, this would cause an artificial increase in the sensitivity curve and therefore these numbers should not be less than zero. As an alternative, the final results are averaged over the three energy bins with a distribution similar to the inverse beta decay energy plot. The result for the entire 11.38 LAMPF-days is:

A) Bin 1: 0.1 (±1.5)
B) Bin 2: 0.3 (±3.0)
C) Bin 3: 0.1 (±2.4)

8. The central detector's response to low energy electrons. This
response includes the "4-AND" detection efficiency for inverse beta decay electrons along with the FAST LOGIC tank-and efficiency of 88.7%. It also includes the redistribution of the electron energy spectrum away from the actual "input" event distribution for inverse beta decay electrons. Shown in Fig. 85 is the Monte Carlo generated event distribution for inverse beta decay electrons. This "true" input electron distribution takes into account the inverse beta decay kinematics and reveals the high energy slope down to 51 MeV, which is due to the cutoff in neutrino energy at 52.8 MeV. The electrons selected according to this distribution are then put through a EGS Monte Carlo model of the central detector and a "4-AND" trigger simulation program. The resultant energy is plotted in Fig. 86. The ratio, in the number of events in each energy bin of the "output" spectrum (Fig. 86), divided by the number of events in the same energy bin of the "input" spectrum (Fig. 85), gives the detector's response for that energy bin. Note, that if this detector response were not taken into account, the systematic redistribution of events in the "output" energy plot might be wrongly attributed to the oscillation phenomenon. The response results for each energy bin are:

A) Bin 1 : 0.247 (±0.012)
B) Bin 2 : 0.337 (±0.010)
C) Bin 3 : 0.088 (±0.003)
Figure 85

Histogram of the "input" total energy values for inverse beta decay electrons.

Figure 86

Histogram of the "output" total energy values for inverse beta decay electrons after passing through an EGS Monte Carlo.
The 3% to 4% errors are statistical, but another 5% systematic uncertainty is included to account for any differences that may occur between the trigger simulation program and the actual hardware performance of the FAST LOGIC and the trigger processor modules.

6.5.2 Likelihood Results

From the 11.4 LAMPF-day run the 90% confidence limit for the E645 detector is shown in Fig. 87. The outer limits of this curve are \( \sin^2 \theta = 0.05 \pm 0.01 \) (systematic) (for \( \delta m^2 = 1.7 \text{ eV}^2 \)) and \( \delta m^2 = 0.20 \text{ eV}^2 \pm 0.05 \) (systematic) (for \( \sin^2 \theta = 1 \)).

The broad band for the sensitivity curve reflects the systematic uncertainty for the likelihood fit. All of the systematic errors described above are added in quadrature; the number of neutrinos produced (\( \pm 12\% \)), the number of free proton targets in the detector (\( \pm 5\% \)); the cross sections (\( \pm 20\% \)), and the triggering efficiency (\( \pm 5\% \)). The two outside boundaries of the shaded sensitivity curve represent the combined 1\( \sigma \) variation in the input parameters used.

A detailed attempt to obtain the sensitivity limits for future running conditions is shown in Fig. 88 and Fig. 89. The two curves in each figure are labeled as the "best" and "worst" sensitivities that E645 will be able to accomplish. The "worst" curve can be reached if the running conditions stay basically unchanged from the engineering run. The only changes are to use of a "3-AND" trigger, which improves the inverse beta decay trigger of 0.454, and a FAST LOGIC efficiency of
Figure 87

The $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ sensitivity curve with 1σ systematic error bars, for the 11.4 day engineering run.
Figure 88

The projected "best" and "worst" $\bar{\nu}_\mu \to \bar{\nu}_e$ sensitivity curves with $1\sigma$ systematic error bars, for a 180 (133 live) day data run.
Figure 89

The projected "best" and "worst" $\bar{\nu}_u + \bar{\nu}_e$ sensitivity curves with 1σ systematic error bars, for a 360 (265 live) day data run.
0.961 instead of 0.887. Also, all the low "muon-peak" scintillator tanks used during the engineering run were replaced and therefore the software low "muon-peak" cut is eliminated. Otherwise, there is an assumed 0.67 cosmic-ray background events per LAMPF-day, twice the "4-AND" rate, and no additional neutron shielding, which implies the need for the severe PDT "dE/dx" chi-squared cut as applied in the engineering run analysis. The resulting software efficiency is 0.338.

The "best" curve is generated for a decreased cosmic-ray background rate down to the negligible value of 0.05 events per LAMPF-day. This is accomplished by the addition of cosmic ray overburden. Also the high beam associated neutron background is assumed to be eliminated and therefore no PDT "dE/dx" cut needs to be made. This curve implies a software efficiency of 0.677.

In Fig. 88 these curves are presented for a real running time of 180 days which, due to LAMPF's down time and detector dead time, is reduced to 133 live LAMPF-days. In Fig. 89 the run is taken to last for two years or for 265 live LAMPF-days. Also seen are the systematic error bars for each curve, which were assumed to be the same as the values taken for the engineering run.

It is seen that for E645 to overlap with the Bugey positive oscillation result under the "worst" case conditions, a run of at least two years is needed.

And finally, a unique result from the 11.4 LAMPF day engineering run is the sensitivity curve for the exclusive Majorana oscillation mode $\nu_e \rightarrow \bar{\nu}_e$. The $\nu_e$ spectrum from the beam stop shown in Fig. 4 in
Chapter 2, is on the average distributed lower in energy than the $\bar{\nu}_\mu$ spectrum. This causes a lower average cross section for the $\nu_e \to \bar{\nu}_e$ induced $\bar{\nu}_e p$ reactions than for a $\bar{\nu}_\mu \to \bar{\nu}_e$ induced $\bar{\nu}_e p$ inverse beta decay process. This in turn causes the electron event distribution to also be peaked lower in energy and therefore results in a lower "4-AND" inverse beta decay trigger efficiency. The $\nu_e \to \nu_e$ curve is shown in Fig. 90 and covers a smaller area on the parameter space plot. Also note that the parameters for the Majorana theory $\delta m^2_{\text{MAJ}}$ and $\sin^2 2\theta_{\text{MAJ}}$ are different than the Dirac parameters $\delta m^2$ and $\sin^2 2\theta$, presented in earlier plots.
Figure 90

The $\nu_e - \bar{\nu}_e$ sensitivity curve with 1σ systematic error bars, for the 11.4 day engineering run.
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