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*A Photon Detector System for the
Search for the Rare Muon Decay $\mu \rightarrow e\gamma$*

Los Alamos
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*A Photon Detector System for the
Search for the Rare Muon Decay $\mu \rightarrow e\gamma$*

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A PHOTON DETECTOR SYSTEM FOR THE SEARCH FOR
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by

Leo Anthony Van Ausdeln

ABSTRACT

An innovative and state of the art pair spectrometer system to measure the photon component of μ^+ decay to obtain an improved branching ratio limit for the decay $\mu \rightarrow e\gamma$ is investigated. Analysis algorithms are developed and an experimental inner bremsstrahlung spectrum is obtained and agrees well with Monte Carlo simulations. Background sources are investigated and found to be highly suppressed at various stages of acquisition and analysis.

CHAPTER I

INTRODUCTION

Since the discovery of the muon in 1936 [1], it has become a primary tool for investigating the weak interaction. Studies of (V-A) structure [2] in muon decay and nuclear beta decay led to the establishment of the weak interaction as one of the four fundamental forces of nature. Two-component neutrino theory and parity non-conservation were well established through the study of the asymmetric positron distributions of muon decay [3]. Neutrino interactions were observed in a 1962 experiment [4] where neutrinos were produced through pion decay. The observation of muons and the absence of electrons in the interaction products established that the muon neutrino produced in pion decay was indeed distinct from the electron neutrino. This confirmed an earlier $\mu \rightarrow e\gamma$ search [5] that observed no such decay at the 10^{-4} level. These and other results have led to the development of the Standard Model [6,7,8] of electroweak interactions which has shown remarkable agreement with all experimental measurements. One feature of the Standard Model is lepton family number conservation which, for massless neutrinos, forbids the decay $\mu \rightarrow e\gamma$. Observation of this decay would therefore necessitate extending the Standard Model, while non-observation of the decay at improved levels would provide valuable limits on possible extensions to the Standard Model. The most recent measurement of the $\mu \rightarrow e\gamma$ branching ratio sets an upper limit of 4.9×10^{-11} . It was obtained by the Crystal

This dissertation follows the style of *Physical Review Letters*.

Box collaboration [9,10] at LAMPF (Los Alamos Meson Physics Facility), the predecessor to MEGA (Muon decays to Electron + GAMMA), the collaboration with which this research is performed. MEGA hopes to improve the branching ratio by two orders of magnitude. Such an improvement can have several theoretical benefits: MEGA would be sensitive to a right handed vector boson (W) mass of 2 TeV [11]; and lepton constituent masses of 4×10^8 GeV [12]. These benefits and other implications are discussed further in the next chapter.

Any rare decay search has two principle experimental objectives; the identification and classification of decay candidates and the identification and elimination of background, or non-candidate events. In an experiment such as MEGA, where the experimental design assumes that no candidate decays will be observed, the decay candidates observed are those background events that are kinematically indistinguishable from legitimate candidates. As we hope to, but expect not to, observe any $\mu \rightarrow e\gamma$ decays, the overall goal is to improve the branching ratio for this decay. Since the sources of backgrounds are known, we may estimate the number of background events that will be indistinguishable from legitimate $\mu \rightarrow e\gamma$ decays for a given number of muon decays observed. This number depends on the resolution of our detector for the observables of interest. Improved resolution increases the efficiency with which we distinguish background events from legitimate candidate decays. For Crystal Box, $\sim 10^{11}$ decays were observed over $\sim 10^7$ seconds before any background events appeared in the kinematic acceptance of the search. For MEGA, with the improvements in various aspects of the detector system as well as an increased beam rate, $\sim 10^{13}$ decays may be observed over approximately the same time before background events

occur. The point at which background events begin to appear is important because the branching ratio in a background-free experiment is proportional to $\frac{1}{N}$, where N is the number of observed decays. In a background limited environment, as we have once background events begin to occur as candidate decays, the branching ratio improves as $\frac{1}{\sqrt{N}}$. This is because in a background limited environment, the number of usable decays $N = N(\text{observed}) - N(\text{background})$ is sensitive to the statistics collected. It is therefore not feasible to extend the search into the background limited regime as the branching ratio improves at a much slower rate.

We will search for the decay $\mu \rightarrow e\gamma$ by stopping a 28 MeV/c muon beam in a polystyrene target after which each muon decays via one of two channels: the normal decay $\mu \rightarrow e\nu\bar{\nu}$ and the radiative decay $\mu \rightarrow e\gamma\nu\bar{\nu}$. We therefore must distinguish the $\mu \rightarrow e\gamma$ decay products from those due to the above two decays. This can be accomplished by noting that the $\mu \rightarrow e\gamma$ decay is characterized by three basic signatures: (1) the electron and photon are emitted back to back; (2) they each have an energy of 52.8 MeV; and (3) they are in time coincidence. Thus our detector system must be able to measure time, energy and direction of both of the decay products with good resolution. Some few of these decays may still fall within the resolution of our detector and be indistinguishable from legitimate $\mu \rightarrow e\gamma$ events. The principal source of these "background" events is a random coincidence between a photon from the decay $\mu \rightarrow e\gamma\nu\bar{\nu}$, which occurs in 1.4% of all muon decays, and a "Michel" positron from normal muon decay. It is these background events which ultimately place a limit on the level to which we may measure the branching ratio for the rare decay. For infinitely good detector resolution, we can eliminate all background events

and have no limit to the level to which the search may be extended. Unfortunately, in the real world, there are technological limits on our detector system. The number of useful muon decays we observe before background events become probable is therefore finite.

MEGA is an improvement over previous $\mu \rightarrow e\gamma$ measurements in several respects. First, the entire detector system is placed in a solenoidal magnetic field. This limits decay positrons to the internal portion of the detector, away from the photon detector, allowing separation of the positron and photon detector systems into two independent units. Secondly, the photon is detected by a highly granular set of pair spectrometers, improving the photon energy resolution to $\sim 2.5\%$ from the Crystal Box resolution of $\sim 8\%$. Thirdly, highly granular and very fast MWPC's will be used to measure positron energy to better than 1% compared to the Crystal Box resolution of $\sim 8\%$. Finally, both detector systems, positron and photon detectors, contain highly segmented scintillator components for improved timing. The design goals for the resolutions of measured parameters for MEGA, compared to Crystal Box, are shown in table 1. The photon angular resolution is large (10°) due to scattering of the converted pair in the Pb converter sheets. The Bremsstrahlung veto counters, one at each end of the detector, are used as a time-coincidence veto to suppress random $e\gamma$ coincidences from inner Bremsstrahlung decay. The Bremsstrahlung veto inefficiency should be 0.2, but due to the abundance of spurious muons at the magnet

Table 1. Parameters for $\mu \rightarrow e\gamma$ Experiment (Compared to Crystal Box)

Property	MEGA	Crystal Box
Fractional Positron Energy Resolution	.006	.08
Fractional Photon Energy Resolution	.025	.08
Photon-Positron Timing (ns)	0.8	1.1
Positron Resolution at the Target (mm)	2.0	2.0
Positron Angular Resolution (deg)	0.6	1.3
Photon Conversion Point Resolution (mm)	3	25.
Positron-Photon Angle (deg)	0.6	8.0
Photon Angle (deg)	10.	—
Bremsstrahlung Veto Inefficiency	0.6	0.5
Fractional Solid Angle $\times$ Detection Efficiency	.04	0.2
Muon Stopping Rate ($\times 10^6 \text{s}^{-1}$)	30	0.5
Running Time ($\times 10^6 \text{s}$)	12	2
Branching Ratio Sensitivity	6×10^{-13}	4.9×10^{-11}
Background Events with $\pm 2\sigma$ cuts	2.5	50.

All resolutions are FWHM

entrance, only one of the two veto counters will be used.

The final item in table 1 illustrates a major advantage of MEGA over Crystal Box. Crystal Box became background limited before the quoted branching ratio was achieved, whereas MEGA is virtually background free until the design goal branching ratio is nearly achieved. With improved resolutions as in table 1 MEGA therefore can achieve a branching ratio comparable to the Crystal Box measurement fairly early on and run significantly longer before becoming background limited.

The focus of this dissertation is the photon detector and its performance in a 1990 test run. The detector used at that time was a prototype of the final design and lacked several key components to be discussed later. The detector is evaluated

in terms of its timing, energy and position determination capabilities given the state of the detector in 1990.

Chapter II outlines the Standard Model and details several extensions to the model that predict the $\mu \rightarrow e\gamma$ decay at various levels. Chapter III describes the MEGA detector system, with emphasis on the photon detector. Chapter IV describes the analysis performed in evaluating the photon detector. Chapter V treats 52.8 MeV Monte Carlo generated photons in light of the analysis of chapter IV. Chapter VI discusses the implications of the analysis and possible improvements.

CHAPTER II

THEORETICAL BACKGROUND

II.1 The Standard Model

The four fundamental forces in nature are the gravitation, electromagnetic, strong nuclear and weak nuclear forces. It has long been the goal of physicists to unify the behavior of these forces into a single comprehensive theory. The development of Quantum ElectroDynamics (QED) [13] resulted in a description of electromagnetic phenomenon remarkably in agreement with all available experimental data. Physicists were successful in their formulation of quantum electrodynamics through the use of the gauge invariant symmetry group $U(1)$. The principle of invariance under global, and ultimately local, gauge transformations has been a crucial one in the development of the Standard Model. Global gauge invariance is required in QED to conserve charge. The mediating boson associated with the generator of the group, required by local gauge invariance, is the massless photon. Another crucial principle, that of renormalizability, is an important one in the Standard Model as higher order diagrams would contribute divergences that would make the theory ultimately non-physical were it not renormalizable.

The success of QED ultimately led to the development of the Standard Model [6,7,8] by Weinberg, Salam and Glashow. This theory, like QED, has been remarkably successful in its description of available experimental data. The complete model is described by the symmetry $SU(3)_C \times SU(2)_W \times U(1)_Y$. The constituents of the standard model are listed in figure 1.

The $SU(2) \times U(1)$ symmetry describes the electroweak sector of Standard Model. The $SU(2)$ symmetry introduces 3 mediating bosons: the charged $W^\pm$ and the neutral W^0 . The 3 resulting weak bosons which mediate the weak interaction are predicted to be massless in a non-abelian Yang-Mills [14] formalism. Spontaneous symmetry breaking induced by a Higgs field is required to give mass to these bosons and consequently introduces a Higgs boson. This same technique is used to give the fermions of the electroweak sector their masses. Unfortunately manifest gauge invariance is lost in this process. Although the local gauge invariance is spontaneously broken, t'Hooft [15] showed that it remains renormalizable.

There are 12 known fermions; six quarks and six leptons, listed in the top three rows of figure 1. The quark states of figure 1 occur three times, once for each of the three quark colors. In the Standard Model the fermions occur in left handed $SU(2)$ isodoublets and right handed isosinglets.

The $SU(3)$ symmetry group describes the color interactions of the strong force. Eight gauge bosons, designated gluons, are postulated to mediate the strong force. These correspond to the eight generators of the $SU(3)$ group. The "charge" of the symmetry group is color, analogous to the electric charge of the $U(1)$ group in QED. Unlike the photon of QED, gluons undergo self-interactions because they themselves carry color charges. At short distances, the color interactions among the quarks is weak. This is referred to as "asymptotic freedom". At longer distances, the gluon mediated quark interaction increases linearly with distance, leading to the phenomenon of "quark confinement". As quarks are separated, the quark interaction produces

$$\begin{array}{ccccc}
\begin{pmatrix} u \\ d' \end{pmatrix}_L & \begin{pmatrix} \bar{e}^- \\ \nu_e \end{pmatrix}_L & (u)_R & (d')_R & (e^-)_R \\
\begin{pmatrix} c \\ s' \end{pmatrix}_L & \begin{pmatrix} \bar{\mu}^- \\ \nu_\mu \end{pmatrix}_L & (c)_R & (s')_R & (\mu^-)_R \\
\begin{pmatrix} t \\ b' \end{pmatrix}_L & \begin{pmatrix} \bar{\tau}^- \\ \nu_\tau \end{pmatrix}_L & (t)_R & (b')_R & (\tau^-)_R \\
\gamma & g & W^\pm & Z^0 &
\end{array}$$

Figure 1. Constituents of the Standard Model : Fermions in Top Three Rows; Gauge Bosons in Bottom Row

quark-antiquark pairs to form mesons from the separated quarks. This phenomenon leads to “quark jets” in various high energy physics experiments.

Quark mixing was first postulated by Cabibbo [16] and led to the introduction of a small “Cabibbo” mixing angle to describe the existence of the d' and s' quarks as admixtures of the d and s quark mass eigenstates. This explained much of the strangeness violating $\Delta S = \pm 1$ and strangeness conserving $\Delta S = 0$ behavior in hadronic weak interactions through Cabibbo favored and Cabibbo suppressed transitions among the first two quark families. This concept was later generalized to include the t and b quarks in the Cabibbo-Kobayashi-Maskawa [17] mixing matrix:

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

This unitary matrix involves 3 mixing angles and a single phase. The values of the individual elements are determined experimentally and are not predicted by the Standard Model. The elements involving the as yet unobserved t quark are uncertain, and were obtained indirectly through the requirement of unitarity. CP violation can be included in the Standard Model by introducing a phase in the Kobayashi-Maskawa matrix. No mixing has been observed between the individual lepton families. Such mixing would permit the $\mu \rightarrow e\gamma$ decay through mixing muon and electron fields. A Kobayashi-Maskawa like lepton mixing with massive neutrinos is discussed in the next section as a possible Standard Model extension.

The top three rows of figure 1 illustrate an experimentally determined grouping of leptons and quarks into three separate families within the Standard Model. The occurrence of three families is not part of the Standard Model but is a purely experimental result, just as is the case for parity violation. Another experimental phenomenon not accounted for in the Standard Model is the apparent conservation of lepton family number. Both multiplicative and additive conservation schemes have been proposed. The multiplicative scheme of Konopinski and Mahmoud [18] fails in its prediction of a branching ratio of $\frac{1}{2}$ for $\mu \rightarrow e^- \nu_e \bar{\nu}_\mu$. The additive scheme of Schwinger [19] works for all observed weak phenomenon. We will discuss only the additive scheme here. An illustration of this conservation is seen in the normal decay of the muon.

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

$$0 = (+1) + (-1) + (0) : L_e \quad \sum L_e = \text{constant}$$

$$1 = (0) + (0) + (+1) : L_\mu \quad \sum L_\mu = \text{constant}$$

$$0 = (0) + (0) + (+0) : L_\tau \quad \sum L_\tau = \text{constant}$$

If one assigns separate lepton numbers to each family in the decay, assigning +1 to particles and -1 to anti-particles, the additive conservation scheme works.

Noether's theorem states that for a given physical process whose Lagrangian is invariant under a given symmetry operation there exists a conservation principle. Conservation of linear momentum is a consequence of translational invariance. Conservation of angular momentum is a consequence of rotational invariance. Energy conservation is a consequence of the invariance under time translations. The conservation of charge is a consequence of the global gauge invariance of the electromagnetic interaction. No such invariance principle is known to exist for the conservation of lepton family number. The search for lepton family number violating processes is therefore fundamental to the limitation and possible extension of the Standard Model. A positive $\mu \rightarrow e\gamma$ signal would have important consequences for the Standard Model, whereas an improved branching ratio for the $\mu \rightarrow e\gamma$ decay would further constrain possible extensions to the Standard Model.

II.2 Extensions to the Standard Model

In spite of the success of the Standard Model, it has some drawbacks. It contains a large number of seemingly arbitrary parameters only obtainable empirically. It does

not explain CP violation in K_L^0 decay. It must be built into the Standard Model by adding a phase to the Kobayashi-Maskawa matrix. Lepton family structure and lepton conservation within each of these families is not explained in the Standard Model. The Standard Model is not symmetric. Left-right symmetric models have been proposed for high energy behavior, introducing much more massive right-handed equivalents to the $W^\pm$ and Z^0 bosons of figure 1. Unification with the gravitational domain is not part of the Standard Model. Clearly, extensions to the Standard Model are necessary if we wish to eliminate the above problems. Several extensions have been proposed that would make observation of $\mu \rightarrow e\gamma$ possible at various levels. We review some of these below.

II.2.1 Massive Neutrino Model

The simplest and most straightforward extension to the Standard Model is to make the three generations of neutrinos massive. Cheng and Li [20] calculate the branching ratio assuming neutrino mixing as

$$\frac{\Gamma(\mu \rightarrow e\gamma)}{\Gamma(\mu \rightarrow e\nu\bar{\nu})} = \frac{3\alpha}{32\pi} \sum_{i=1}^3 [|U_{\mu i}^* U_{e i}|^2 \frac{m_i^4}{M_W^4}]$$

summing over the three known lepton families. The U_{ij} terms are the leptonic equivalents of the Kobayashi-Maskawa quark mixing matrix given above. Experimental upper limits of ~ 9 eV [21] on the ν_e mass, 0.27 MeV [22] on the ν_μ mass and 35 MeV [23] on the ν_τ mass make only the τ term above non-negligible. The current experimental limit on $|U_{\mu\tau}^* U_{e\tau}|$ was obtained by Cnops et al. [24] and is

$$|U_{\mu\tau}^* U_{e\tau}| < 2.5 \times 10^{-3}$$

The current value of the W mass [25] is 80.2 GeV. Then the branching ratio is

$$\frac{\Gamma(\mu \rightarrow e\gamma)}{\Gamma(\mu \rightarrow e\nu\bar{\nu})} < 2 \times 10^{-20}$$

This is extremely small and not within the domain of MEGA.

The above calculation may be performed equivalently for right-handed neutrinos and bosons in a left-right symmetric model.

II.2.2 Horizontal Gauge Bosons and Technicolor

Another extension to the Standard Model that allows $\mu \rightarrow e\gamma$ is the postulation of a horizontal gauge boson [26]. This boson would mediate flavor changing transitions between lepton families without changing T_3 isospin. Extended Technicolor models [27] introduce the technicolor interaction, analogous to color, and a collection of new particles such as the leptoquarks, technifermions and a set of bosons to couple different lepton families together. In these extensions the decay $\mu \rightarrow eee$ is a more prominent decay channel. $\mu \rightarrow e\gamma$ is a radiative correction to $\mu \rightarrow eee$ and is suppressed by a factor of α .

II.2.3 Supersymmetric Models

The symmetries traditionally used by particle physicists relate bosons to bosons and fermions to fermions. A "supersymmetric" model [28] constructed to relate bosons and fermions introduces a supersymmetric partner to each fundamental particle in the Standard Model. $\mu \rightarrow e\gamma$ puts stringent limits on the mass difference between a given lepton and its supersymmetric partner, or slepton. Nanopoulos [29] calculates a difference of

$$\frac{\Delta m_{sl}^2}{m_{sl}^2} \sim 10^{-3}$$

from the $\mu \rightarrow e\gamma$ branching ratio upper limit. Since this branching ratio is proportional to $\Delta m_{s'l}^2$, an improvement of two orders of magnitude in the branching ratio upper limit introduces more stringent limits on supersymmetric masses.

II.2.4 String Models

Arnowitt and Nath [30] have suggested a string model with E_6 symmetry. The Lagrangian in this case ultimately reduces to $SU(3) \times SU(2) \times U(1)$ at low energies. Positive signals for $\tau \rightarrow \mu\gamma$ and $\mu \rightarrow e\gamma$ are predicted with relative strengths

$$B(\tau \rightarrow \mu\gamma) \sim 2 \times 10^5 B(\mu \rightarrow e\gamma)$$

The current direct experimental limit on $\mu \rightarrow e\gamma$ of 5×10^{-11} implies a $B(\tau \rightarrow \mu\gamma)$ limit of 1×10^{-5} , a factor of ~ 2 worse than the direct experimental value [31] of 4.2×10^{-6} . This is certainly in the domain of MEGA.

II.2.5 Grand Unified Theories

Physicists have long sought a mechanism to unify the color $SU(3)$ group and the electroweak sector into a single symmetry G .

$$G \supset SU(3)_C \times SU(2)_W \times U(1)_Y$$

Some of the model extensions already mentioned make attempts at this. Georgi and Glashow [32] have shown that the simplest such symmetry is $SU(5)$. $SU(5)$ postulates the existence of two superheavy charged gauge bosons, X and Y , which couple quarks and leptons. An exciting implication of this is the decay of the proton via $p \rightarrow \pi^0 e^+$ and other less dominant modes. Marciano [33] predicts the lifetime as $4.5 \times 10^{29 \pm 1.7}$

years. Various proton decay measurements [34] have not observed such decays and set limits on the lifetime of $10^{30} - 10^{32}$ years. This discrepancy suggests either that the X and Y bosons must have masses $\sim 10^{15}$ GeV or that a higher symmetry such as $O(18)$, $SO(10)$ or E_6 is necessary.

II.2.6 Summary

It is clear that, in spite of its success, the Standard Model is incomplete. Many extensions, not all mentioned here, offer hope of a more complete theory. The search for lepton family number non-conserving rare decays can be vital in completing the Standard Model. As such, physicists should press their investigations of these rare decays.

CHAPTER III

EXPERIMENTAL EQUIPMENT

Our experimental apparatus consists of six principle subsystems, listed chronologically for a given muon decay:

1. The muon beam delivery system;
2. The superconducting magnet;
3. The stopping target;
4. The positron detector system;
5. The photon detector system;
6. The trigger and data acquisition systems.

Figure 2 shows the detector setup contained in the magnet, including the target, the positron and photon detectors.

The beam enters the 1.5T superconducting solenoidal magnet and is stopped in the mylar target at the center of the magnet. A particular muon then decays with a mean life of $2.2 \mu\text{s}$ via one of two channels: the normal muon decay $\mu \rightarrow e\nu\bar{\nu}$ or the radiative decay $\mu \rightarrow e\gamma\nu\bar{\nu}$. We do not detect neutrinos. The decay positrons are tracked as they orbit through the positron detector which is contained within the inner portion of the magnet. The positron detector consists of eight cylindrical MultiWire Proportional Counters (MWPCs), one located concentric to the z axis of the system surrounding the target and the other seven placed symmetrically about the first as shown in figure 3. The positron detector also contains scintillators located

Figure 2. Magnet-Detector Setup

at either end of and enclosed within the central MWPC to obtain timing information. The summer 1990 run at LAMPF was intended to be the final prototype testing and development run for the detector systems so that only three of eight electron MWPC's and the upstream scintillators were installed.

Decay photons are detected in the photon spectrometer by use of Pb converter foils and three layered drift chambers to track the resulting $e^+ e^-$ pairs as well as scin-

tillators to provide timing information. Only the innermost of the three spectrometer layers was installed for testing in 1990.

The following sections of this chapter describe the various detector components in detail.

Figure 3. Detector Setup, End View, Looking Into the Beam From the Downstream End

III.1 The Muon Beam and Delivery System

Muons are produced as a secondary beam at LAMPF from a primary beam of 800 MeV protons that is obtained from the LAMPF LINAC. The LAMPF proton beam is pulsed at 120 Hz with a 6-7% duty factor, each pulse containing a 201 MHz substructure of individual proton packets. The secondary beamline, from target to solenoid, is shown in figure 4.

Figure 4. Stopped Muon Channel Beam Line

The protons are incident on target A2, composed of graphite, and produce primarily π^+ 's, π^- 's and an assortment of light nuclei. Most of the π^+ 's exit the target

while a smaller number decay into muons via $\pi^+ \rightarrow \mu^+ \nu$. The majority of these muons decay into positrons via $\mu^+ \rightarrow e^+ \nu \bar{\nu}$ which escape the target, while a small fraction of muons produced close to the target surface escape the target prior to decaying to positrons. The particles coming out of the target, which comprise the outgoing beam, are focused by quadrupole magnets into a pair of bending magnets, BM01 and BM02 in figure 4. The bending magnets are set to select a specified momentum component from the incoming beam. In the case of a π^- beam 135 MeV/c is selected while 28.5 MeV/c is selected for the surface μ^+ component. The resulting beam is then directed along a series of bending and quadrupole focusing magnets into the MEGA cave, one of three experiment channels in the Stopped Muon Channel (SMC) area of LAMPF.

The muon beam entering the cave area is $\sim 90\%$ positrons and $\sim 10\%$ μ^+ 's. The beam next encounters the separator shown in figure 4. The separator consists of parallel plates to provide an electric field and magnetic field coils to provide a magnetic field perpendicular to the electric field. The fields are set to produce electric and magnetic deflections of the beam in opposite directions, with the magnetic deflection upward and the electric deflection downward. The idea is to pass the muon beam component undeflected while deflecting the positron component downward and out of the beamline. A simple calculation shows that the separator will pass the beam component for which $\frac{E}{B} = \beta$. For the muon component $\beta = .26$, while for the positron component $\beta = .9998$, so the separation is very effective. The beam constituents on target after the separator have been measured as 90% muons and 10% positrons. The fields necessary to accomplish this task in 1990 were a magnetic field of ~ 1 kG and an electric field resulting from a voltage of ~ 200 kV across a plate separation of 15 cm.

Figure 5. Beam Slit Settings

Following the separator, the muon beam is then refocussed through two quadrupole magnets and into the solenoid.

Also shown in figure 4 are the beam slits, labeled MS01, which are used to control beam intensity into the solenoid. Settings, read from a Digital Volt Meter in the SMC counting house, vary from 6.0, fully open, to 9.0, almost fully closed. A setting of 9.3 is fully closed, but 9.0 was the minimum setting used in 1990. Figure 5 shows the muon stopping rate in the target for MS01 settings varying from 6.0 to 9.0 measured early in the 1990 run at LAMPF. The maximum muon stopping rate was measured with MS01 set to 6.0 and 1000 μA of proton beam current incident on target A2. The stopping rate was then measured as 3.1×10^7 using an ionization

chamber in place of the target. During data acquisition the current was typically 920 μA scaling this number to 2.9×10^7 .

Figure 6. Degradation Curves

Also installed in the beamline within the MEGA cave are several degraders. These are used to slow the beam through $\frac{dE}{dx}$ ionization so that a higher percentage of the beam will be stopped in the target. Early in the 1990 run, beam intensity was measured with an ionization chamber to determine the effect of changing the thickness of the degrader on the intensity for several different slit settings. Mylar degrader material was used. The resulting beam intensities, shown in figure 6, indicate that

.30 mm of degrader, combined with a .50 mm target, stop over 99% of the muons in the target. The degrader placement was 0.01 mm at the entrance of the separator, 0.02 mm at the exit of the separator, and the remaining 0.27 mm located 44.75 cm prior to the target on the end of the helium filled target bag as shown in figure 7. Helium was used to inflate the target to a rigid state to minimize beam stopping interactions prior to reaching the target. The use of helium also minimizes multiple scattering of decay positrons orbiting through the target bag.

Figure 7. Electron Chamber - Side View : Showing Central e^+ (SnowWhite) and Two Outer e^+ MWPC's (Dwarves)

The beam spot size at the target in 1990 was determined by placing a planar MWPC at the target position. This chamber contains two separate planes, one with vertical wires and one with horizontal wires for both x and y readout of the beam

profile. The wires are 0.5cm apart and are used to obtain the beam spot size by measuring the count rate of each wire. The beam tune is further optimized by measuring the spot size while adjusting settings of individual beamline components. The optimized beam spot size, shown in figure 8, is 2.5cm by 3.5cm FWHM.

Figure 8. Beam Spot Size

III.2 The Magnet

The entire detector system is placed within a superconducting solenoidal magnet with ~ 15 kG central field. The magnet, with enclosed detector system, is shown in

Table 2. Present Parameters of the MEGA Magnet

Clear Bore Diameter	1.85 m
Overall Length (iron)	4.05 m
Central Field	1.5 T
Conductor Current	1118 A
Total Stored Energy	8.8 MJ
Total Inductance	14 Henrys
Total Helium Volume (including resevoir)	3950 l
Operating Heat Load	30 l/hr He (4.2°K) 30 l/hr N ₂ (79°K)
Total Cooldown Time	30 days
Current Charging Time	20 min
Total Weight of Iron	180 tons
Winding Configuration	Pancake
Conductor Type	Cryostatically stabilized composite, multi-filament wire
Conductor Copper-to- superconductor(Nb ₃ Ti) ratio	20:1
Conductor Current Density	2750 A/cm ²
Conductor length	28.3 km
Conductor Weight	10,500 kg

figure 2. It was obtained from the Stanford Linear Accelerator Center and modified to suit MEGA. The magnet's characteristics are listed in table 2. It consists of 3 donut-like sections, each with a cryostat containing the superconducting coils that are surrounded by a section of magnet iron, and 2 end caps. The resulting magnetic field is primarily along the z-axis along the beam direction.

Each endcap has a nosecone placed at its center. Each nosecone supports the electron scintillators, Pb and ring counter so that they are positioned properly when the magnet is closed. The downstream nosecone also supports the target bag containing the target and degraders. These systems are discussed in more detail in the next section.

Figure 9. B-map : Total Field Strength versus Position (B in Gauss; R,Z in cm)

In 1987, the magnet was mapped in detail. A probe was attached to a disc-like assembly allowing a field measurement along a 5 cm grid. Measurements of B_r and B_z were taken at 5 cm steps along z from -102 cm to 102 cm and along r from 0 (magnet axis) to 91.4 cm. A number of azimuthal angles were measured from which the field was found to be azimuthally symmetric. Figure 9 shows the resulting field map obtained, assuming azimuthal symmetry. While the field strength varies widely near the cryostats, the field within a 40 cm radius varies at most 10 gauss/cm.

III.3 The Stopping Target

The muon stopping target used during data acquisition was a 5 cm radius .051 cm

thick mylar ($CH_{1.1}$) planar disk placed at the magnet center and oriented normally to the incident beam. It was situated at the middle of a cylindrical, helium filled plastic bag that attached to the downstream nosecone so that, when the helium bag was inflated and rigid and the magnet closed, the target was properly situated at the magnet center. The beam degrader is placed on the end of the target bag so that the beam encounters it before the target. The radius of the target was chosen to be larger than the incident beam spot and the thickness was chosen in order to stop as much of the incident beam within the target as practical while minimizing background from Michel positrons annihilating in flight while traversing the target. This source of background photons is discussed in the next chapter.

A second target was used for pion data acquisition. While the muon target was primarily a stopping target, the pion target was a capture target. The incident π^- must be captured by a hydrogen atom to initiate the sequence $\pi^- + p \rightarrow \pi^0 + n$ followed by $\pi^0 \rightarrow 2\gamma$. We therefore used a cylindrical, 5 cm radius, 10 cm thick polyethylene (CH_2) target with a high concentration of hydrogen and a low Z contaminant.

Ultimately, the muon stopping target will be a long elliptical disk tipped at a steep angle to the beam as in figure 2. This is done primarily to distribute the stopped muons over a wider area, making a thinner target adequate. This presents a typical decay positron with less mass to traverse as it leaves the target, generating less background. Also, since background production increases with material traversed, some photon background will be produced by Michel positrons orbiting in the target plane. Tipping the target results in redirecting much of this background toward

the farther ends of the photon detector and away from the central region where the $\mu \rightarrow e\gamma$ data will be taken.

III.4 The Positron Detector System

The complete positron detector, as shown in figure 2, consists of 2 major subsystems: 8 MWPC's to determine positron trajectories and scintillators to establish timing. Figure 7 shows a more detailed view of the positron detector system.

The MWPC's consist of a central chamber, designated as Snow White (SW) and seven smaller chambers, designated as Dwarves, located symmetrically about SW. Figure 2 shows the relative placement of these chambers while figure 3 shows an end view including the electron MWPC's and an energetic $\mu \rightarrow e\gamma\nu\bar{\nu}$ event. SW is positioned along the z-axis and encloses the target. The dwarves are placed symmetrically about SW at a radial position of 19.1 cm. The chambers must be of high granularity and low mass to accommodate the high rates expected while minimizing background due to positrons traversing the chamber mass. Singles rates were measured as high as 400 MHz instantaneous in the MWPCs in 1990 under maximum beam intensity. Each MWPC is 1.26 m in length with two cathode foil planes separated by 3.5 mm with an anode wire plane at the midplane of the cathode foils. The anode wire plane is at a 6 cm radius for the dwarves and 11 cm for SW and consists of wires spaced 1 mm apart. Electrostatic deflection of the wires when the chamber is charged results in significantly asymmetric MWPC cells particularly in the center third of the chamber. This is remedied by placing eight 0.6 mm glass beads equally about the diameter of the chamber. A 100 μm polyester filament is

wrapped around the chamber and epoxied to the beads to supply adequate restraint of the anode wires. Four such garlands are placed at $z=\pm 12.6\text{cm}$ and $\pm 37.8\text{cm}$ so that each wire is supported at four places along the length of the chamber in addition to the ends at $z=\pm 63\text{cm}$. The anode wires are $15\text{ }\mu\text{m}$ Au-plated tungsten strung with 28g tension. The wires are mechanically wound onto the ceramic endpieces which are mounted onto either end of an aluminum rod to support wire tension during construction and bench testing.

Figure 10. Unwrapped View of e^+ MWPC Hit

Both cathode foils are $25\mu\text{m}$ thick kapton with a 200 nm copper coating on one side. The copper surface of each foil is etched with 3mm wide strips to provide additional position information. The cathode strips are angled so that each strip wraps around the chamber exactly once, providing unambiguous position information for

each wire. Cathode strips are angled oppositely for the two foils, providing two independent position determinations to correlate with the anode wire hit. A legitimate hit is therefore signified by the three-fold intersection of an anode wire with inner and outer cathode strips. Figure 10 shows an unwrapped MWPC indicating a hit at the intersection of an anode wire and two cathode strips. The cathode strips are split at the midpoint of the chamber and are read out independently at each end. Each chamber is operated with a 80/20, CF_4 /isobutane gas mixture. The chamber foils are supported during operation by the maintenance of differential gas pressures. This required the development of a complicated gas system to provide both fast gas flow and differential pressures for the integrated system of eight MWPC's.

After construction, bench testing with a source and conditioning, a given MWPC is inserted into an aluminum cylinder, designated as the "tension shell". The tension shell is designed to contain all eight MWPCs and provide support for anode wire tension. This allows the removal of the aluminum tension support rod inserted into each MWPC during construction. The tension shell with MWPC's contained is then inserted within the innermost portion of the photon chambers already positioned within the magnet.

The electron scintillators consist of 176 scintillators, each .63cm wide, .9 cm thick and 30 cm long comprising two separate cylindrical scintillator banks. The sides are angled such that the scintillators can be formed into two cylinders, the .63cm wide surfaces forming the inner and outer surfaces of the cylinder. Each scintillator is individually wrapped in aluminized mylar foil to optically isolate it from its neighbors as well as shield it from outside light. It is read out at one end by a

1.8 m long fiberoptic cable containing 15 individual fibers. The signal is then fed into a photomultiplier tube which transmits the resulting signal via RG-58 cable to the SMC counting house and into dual threshold discriminators and commercially obtained ADC and TDC modules. The scintillator barrels are located as shown in figure 7 and extend from $z=\pm 33\text{cm}$ to $\pm 63\text{cm}$. Directly beneath the scintillator barrels at $z=\pm 62.4\text{cm}$ are the ring counters. Each ring counter is a $\sim 38\text{cm}$ long, .95 cm square rod of scintillator shaped into a ring. The main function of the ring counter is to provide a timing calibration between the photon arm and the electron arm. Each ring counter is located within a slot within the Pb annulus beneath the electron scintillators. There is also a vacuum entrance window located directly below and slightly behind the ring counter. When the beam encounters this window, a small number of muons will stop in the window, emitting positrons when they decay. Timing calibration is performed for both magnet on and magnet off. For the magnet off timing calibration some of the decay positrons will pass through the ring counter, through the electron scintillators and then through the photon scintillators. For magnet on, some decay positrons will pass through the ring counter, and then interact in the neighboring Pb annulus, generating energetic photons that may traverse the photon scintillators. In both cases the signals generated provide a common time base with which to calibrate the electron and photon scintillators.

The ring counter is read out at each end by a fiberoptic light guide identical to the electron scintillator light guide and input to a PMT. The multiplied signal is then sent via RG-58 cable to a NIM bin which uses commercially available CFD's and a meantimer to produce a usable signal. Once all scintillators in the electron

and photon arms are calibrated relative to the ring counter meantime signal, we have a basis for comparison of the timing of photon and positron decay events. The scintillator cylinders are assembled on either nose cone and positioned concentric to the beam axis as shown in figure 7. They are placed so that a given positron produced in the target will orbit through the MWPCs and then through the scintillators as in figure 7. The timing resolution of the electron scintillators was measured at LAMPF in 1990 and found to be 0.6 ns FWHM.

An array of scintillators is installed on both the upstream and downstream nosecones. These are the Internal Bremsstrahlung Veto (IBV) counters shown in figure 2. They are designed to eliminate internal bremsstrahlung $\mu \rightarrow e\gamma\nu\bar{\nu}$ events by correlating high energy (>51 MeV) photons with low energy positrons in the detector. Since most of these positrons will be of low energy, they will orbit in tight helices both upstream and downstream, eventually colliding with the magnet return yolks. The entrance channel (exit channel downstream) will be surrounded by scintillators to form the IBV counters to collect these positrons. These plastic scintillators provide timing information on these low energy positrons to correlate them to photons. Eliminating coincidences within a 20 ns gate opened 2.5 ns after the decay results in a veto of 80% of such inner bremsstrahlung decays while eliminating only 8% of candidate $\mu \rightarrow e\gamma$ photons.

The upstream IBV counter has been found to be saturated by positrons from muon decays along the upstream beamline and is unusable as intended. The veto efficiency is thus lowered to 40% using the downstream IBV counter.

Because of various mechanical and electronic problems, only part of the electron detector system was installed in 1990. Only three of seven dwarves, DW4, DW5 and DW6 in figure 3, were installed for the 1990 LAMPF run. SW was also installed as well as the upstream electron scintillators and ring counter.

III.5 The Photon Detector System

The photon detector consists of 3 distinct, concentric spectrometer layers, each functioning independently except for electronic deadtime when a shower occurs in a given layer. Only the innermost photon detector layer was manufactured and installed for the evaluation and testing described here. This detector layer is located concentric to and outside of the electron detector as shown in figure 7. The magnetic field strength of 15 kG was chosen to preclude any Michel positrons from orbiting as far as the tension shell. This provides the photon detector system with a relatively background free environment in which to function. It consists of 4 principle subsystems:

1. a photon converter consisting of two 0.25 mm thick Pb sheets to induce the transition $\gamma \rightarrow e^+e^-$;
2. an MWPC layer sandwiched between the 2 Pb converter sheets to identify the particular sheet in which the conversion occurred and provide trigger information;
3. three Drift Chambers (DC) positioned concentric to and immediately outside of the converter-MWPC sandwich to track the orbiting e^+e^- pair;
4. a scintillator layer concentric to and immediately inside of the

converter-MWPC sandwich to identify the time of the decay and provide further trigger information.

A detail of the photon detector, including a typical photon decay, is shown in figure 11. Table 3 contains geometric details of the major components for layer one. All detector elements are numbered from zero in increasing order counterclockwise from the zero indicated in figure 3 when viewing the detector from downstream.

Figure 11. Photon Detector Section Showing Energetic Photon Conversion

Table 3. Layer One Photon Detector Geometry (cm units)

	Scint.	Inner Pb	Outer Pb	MWPC	DC1	DC2	DC3
Channels	40			416	208	208	208
Inner Radius	32.0	33.56	34.47	33.87	34.93	35.73	36.53
Outer Radius	33.0	33.88	34.93	34.48	35.73	36.53	37.33
Wire Radius				34.17	35.33	36.13	36.93
Chan. Width	5.04			0.502	1.06	1.09	1.12

III.5.1 Pb Converters

Polar angles of the photon from the target are limited to a range of 10° - 45° . This angular range is selected because Michel positron angles above 45° orbit out of the active detector region in Z before traversing enough of the MWPC's to supply enough information for a good fit to the positron orbit. Angles below 10° consist of positrons that orbit through the active detector region many times before hitting the positron scintillators, resulting in a large uncertainty in the decay time of the original muon.

The $\gamma \rightarrow e^+e^-$ converter material and thickness is chosen so as to maximize pair production probability while minimizing competing processes as well as $\frac{dE}{dz}$ losses of the resultant pair. These competing processes include photoelectric absorption and Compton scattering for the incident photon and bremsstrahlung, Moeller scattering, Bhabha scattering and positron annihilation for the outgoing pair. A high-Z material such as Pb is preferred in order to maximize the ratio $\frac{\sigma_{pair}}{\sigma_{Compton}}$ and to minimize $\frac{dE}{dz}$ losses relative to the pair production yield.

Figure 12. 52.8 MeV Photon Interactions in Pb

To study the behavior of Pb as a converter material, a Monte Carlo simulation program using the EGS4 [35] libraries was used. 5,000,000 photons of 52.8 MeV energy incident normally on Pb converters of various thicknesses were produced. In the actual detector, a photon will traverse several layers of detector material, principally the scintillators and their aluminum support cylinder. The photon showers originating therein will be discussed later. Figure 12 shows the integrated probability of interaction for pair production, Compton scattering and photoelectric absorption as a function of converter thickness for 52.8 MeV photons incident normally on Pb. The solid lines show the Monte Carlo results while the dashed curves are theoretical predictions as tabulated by Storm and Israel [36]. Prior attenuation effects, already

included in the Monte Carlo data, were added to the Storm and Israel numbers. Obviously the photoelectric interaction is negligible compared to pair production, and may be neglected. Hard Compton scattering produces high energy electrons which, in most cases are distinguishable from true e^+e^- pairs in the drift chambers. The few that are misidentified as high energy pairs will degrade the energy resolution. This source of background will be detailed further in the analysis chapter.

Figure 13. e^+e^- Energy Loss

Figure 13 shows energy losses of the pair for various energy loss mechanisms. "Hard" e^+e^- energy losses, losses of more than a few MeV, are primarily from

bremsstrahlung, including both atomic and nuclear contributions. Moeller and Bhabha scattering, though less frequent, may also result in energy loss of several MeV. Low energy bremsstrahlung, Moeller and Bhabha losses are "soft" and are included with $\frac{dE}{dx}$ losses.

Figure 14. Pb Converter Efficiency

Figure 14 shows the integrated pair production efficiency $P_\gamma = \int_0^x p_\gamma dx$ of the converter as a function of converter efficiency. $\eta_{BS} = \int_0^x n_{bs} dx$ shows the integrated fraction of 52.8 MeV pairs that will lose less than 2.5% of their energy. The fraction

$1-\eta_{BS}$ will thus be undetectable as 52.8 MeV pairs, assuming a 2.5% energy resolution. ϵ_γ is the resultant integrated converter efficiency as a function of converter thickness, and is defined as the convolution $\int_0^x p_\gamma n_{bs} dx$. The overall efficiency reaches its maximum for roughly .20 radiation lengths and it reaches 85% of its maximum for 0.09 radiation lengths, the thickness of converter eventually used.

The remaining consideration for our Pb converters is $\frac{dE}{dx}$ ionization energy loss. We can correct for ionization losses and losses from soft bremsstrahlung, Moeller and Bhabha scatters, assuming that we know how much Pb was traversed by the pair after creation. By separating the converter into 2 sheets, with an MWPC in between to determine in which Pb sheet the conversion occurred, we may correct for $\frac{dE}{dx}$ with twice the precision as for the same thickness of converter material in a single sheet. To determine this correction we produce a data set of Monte Carlo photons of 52.8 MeV. If we divide these events according to whether they were produced in the inner or outer Pb converter layers, or in the scintillators or aluminum below them, we determine a correction for each of the three cases. In actuality, the latter of the three cases is experimentally indistinguishable from showers generated in the inner Pb converter annulus. Most of these showers, however, are filtered out by the analysis filter code, as will be seen in the next chapter.

Given the above considerations, and the availability of Pb material commercially, we use 2 Pb-Sb sheets, each .045 radiation lengths (.25 mm) thick. The alloy contained 6% Sb for rigidity as 100% Pb sheets were very soft and were difficult to install and maintain in the geometry required. For this thickness, the EGS4 simulation which produced figures 12-14 indicates that roughly 4% of all converted photons

will be Comptons, while 50% of all pairs will be lost due to bremsstrahlung energy losses, resulting in an overall converter efficiency ϵ_γ of 2.2% for 52.8 MeV photons. For a Monte Carlo simulation of 100,000 photons of 52.8 MeV energy incident, from the target location, we find a converter efficiency of 1.5% for all directions and 2.3% for photons decaying at polar angles between 10° and 45° , the angles ultimately accepted. Further, on average, a pair will lose 1.2 MeV through ionization per Pb converter layer on its way to the drift chambers.

III.5.2 MultiWire Proportional Counter

Sandwiched between the converter layers is an MWPC that is used to determine in which Pb converter layer the conversion occurred. It also assists in locating the vertex of a given shower in the DC's as well as contributing trigger information as detailed later. Simply put, if the MWPC fires in the vertex region of a shower, we may assume the conversion occurred in the Pb converter directly beneath the MWPC. Otherwise the conversion occurred in the other Pb converter directly above the MWPC. Given this information, we know more precisely how much material was traversed by the produced pair on its way to the DC's. We may therefore correct for $\frac{dE}{dx}$ losses by the pair prior to the energy determination performed in the DC's by fitting circular trajectories. Figure 13 indicates that, for .25 mm of total Pb converter, we expect 600 keV $\frac{dE}{dx}$ losses per converted pair and 1.95 MeV bremsstrahlung losses per pair. As already explained, the hard bremsstrahlung losses will not be corrected for and will be reflected by a $\sim 50\%$ efficiency loss of the detector system. Monte Carlo simulations indicate corrections in the .75-1.5 MeV range depending on conversion location and are discussed further later.

The MWPC is comprised of two $51\text{ }\mu\text{m}$ thick aluminum cathode foil planes separated by $.585\text{ cm}$. Midway between these 2 planes is an anode wire plane consisting of 416, $25\text{ }\mu\text{m}$ diameter gold-plated tungsten wires spaced $.52\text{ cm}$ apart. The resulting granularity makes it easier to distinguish the vertex region from secondary MWPC hits caused by looping particle trajectories. Each wire is read out at the downstream end ($z=90\text{cm}$) through a plastic feedthrough designed to transmit the wire signal to electronics mounted on the endcap of the detector while assuring gas tightness.

During assembly, two rohacell cylinders of appropriate radii and length are constructed to support the MWPC cathode foils, as well as the DC foil. Each cylinder also supports a Pb converter sheet. To achieve satisfactory MWPC operation, these cylinders need to be very precise. The precision sought in the 1990 cylinders was $\pm 125\text{ }\mu\text{m}$, but the precision attained was $\pm 400\text{ }\mu\text{m}$, or worse. The completed cylinders are mated in a clean room to the chamber endcaps. The endcaps are machined from aluminum plate and holes are precisely drilled for installation of all MWPC and DC wires. The endcaps are placed on the ends of the cylinders and precisely aligned so that the endcaps are parallel and the wire holes properly aligned vertically. The cylinders are then glued in place. The aluminum scintillator support cylinder for the next outer layer is then lowered around the entire chamber and bolted into place with set screws to provide tension support for the many wires in the chamber. Set screws are adjusted to provide proper alignment.

Installation of the wires is then begun. This is accomplished by using a specially designed and built motor driven apparatus. It was designed to have a wire spool mounted on it. Prior to insertion in the upper hole the wire end is passed through a

thin copper tube and feedthrough assembly. The assembly was designed such that the feedthrough would fit snugly when inserted and seated into the wire hole providing a firm anchor for the wire. The copper tube sits snugly in the outer end of the feedthrough. The copper tube is then crimped at its midpoint to hold the wire in place and allow electrical connections to be attached to the end of the tube. Prior to crimping, the wire is fed thru the feedthrough/copper tube assembly and a thin steel needle is attached to the wire end. The needle is then lowered through the wire hole into the chamber and the feedthrough assembly is firmly seated into the wire hole. The needle is then lowered through the chamber until the wire/needle passes through the lower wire hole, where it is inserted through an identical feedthrough/copper tube assembly. A weight of 135 grams is then attached to the wire end to stretch it. Previous tests have indicated that, if it is not stretched, the wire would slacken enough under the tension, significantly degrading chamber performance. The copper tube is crimped at the upper wire hole, and once the wire has had ample time to stretch, the copper tube in the lower wire hole is crimped prior to removing the weight so that the wire will be properly tensioned. The needle is then passed back to the top of the chamber for insertion of the next wire. This process is repeated for all wires in the MWPC. (A similar process is used to wire the drift chambers.)

When the chamber is completely wired and basic continuity testing is performed, 8 specially designed moonplates are mounted around the circumference of each end-cap. Each moonplate has 8 connectors, each connector holding a 'mother board'. A mother board holds 16 preamplifier chips for MWPC and drift chamber readout. Moon plates are machined from G-10 plate and are roughly crescent shaped. Each

moonplate is mounted several inches from the endcap. This permits access to make wire connections from each copper tube wire readout to its motherboard preamplifier socket. Once these connections are made, the entire chamber is rotated 90° to a horizontal position and inserted into a specially designed carrying apparatus to suspend it for transport to LAMPF.

Figure 15. Photon Wire Chamber Electronics

The flow of MWPC signals is shown in figure 15. The signal output by a given wire is fed into a preamplifier circuit. The preamplifier circuit is shown in figure 16. The preamplifier output is relayed via RG-174 cables to amplifier electronics located outside of the magnet in a relatively field free region. Each signal is input to the

NOTE: ALL DIODES ARE MMBD7000

Figure 16. Photon Wire Chamber Preamplifier Circuit

amplifier-discriminator circuit shown in figure 17. The upper circuit of the figure is used here for the positive polarity pulses output from the preamp circuit. The resulting discriminator output is then routed to the fan-in circuit, shown in figure 18, for distribution to both the first stage trigger module and to a latch module in the fastbus system.

An argon-ethane 57%-43% gas mixture was circulated throughout the MWPC. Originally an argon-ethane-isobutane mixture was used. This mixture has a much faster drift time to the sense wire. The faster gas mixture is necessary to maintain a fast trigger. Due to the poor condition of the rohacell support cylinders in 1990, a gas leak existed between the MWPC and drift chambers. The argon-ethane gas

Figure 17. Photon Wire Chamber Amplifier-Discriminator Circuit : Upper Circuit Used for Positive Polarity Output of Preamplifier Circuit, Lower Circuit Used for Negative Polarity Output of Shaping Amplifier Circuit.

Figure 18. MWPC 4:1 Fan-In Circuit

mixture was therefore used in both the MWPC and the drift chambers. Sense wire charge collection as a function of gas mixture and wire diameter was investigated in 1990 and several other mix ratios were investigated. The 57-43 mixture was found to be optimum for charge collection and stability.

During the first MEGA run cycle in summer 1990, the photon chambers, including the MWPC, were setup and tested in the magnet. A plateau curve was obtained for the MWPC. The ten scintillators and adjacent MWPC sections located symmetrically about the vertical at both the top and bottom of the detector were used, encompassing $\pm 45^\circ$ about the zenith on the top and similarly on the bottom. A cosmic ray trigger was used requiring the traversal of a cosmic ray through both the top and bottom sections. The photon scintillators were assumed to have 100% efficiency. This was used as a gate for the MWPC signal. If a scintillator was hit, the MWPC section directly above it was scanned for a hit, the presence of a hit signifying an efficiency and its absence signifying an inefficiency. The efficiency obtained is not truly indicative of absolute efficiency but relative efficiency as we vary foil voltage to measure the MWPC plateau location. The foil voltage was varied between 1500 and ~ 1900 volts in 25-50 volt steps with efficiencies and inefficiencies recorded at each setting.

The resulting plateau curve is shown in figure 19. The plateau occurs at ~ 1760 volts and is at least 100 volts in width. Due to nonuniformities in the rohacell cylinders supporting the MWPC foil planes, the voltage could not be increased higher without the risk of wire breakage during discharge.

Figure 19. MWPC Plateau Curve

As discussed above, the rohacell cylinders were constructed with a precision of only $\pm 400\mu\text{m}$. This resulted in significant asymmetries and nonuniformities in the halfgap of the MWPC, leading to significant electrostatic breakdown between either foil and a nearby sense wire. Such discharges led to a large number of broken wires thus resulting in general instability, unreliability and low efficiency of the remaining sections of the chamber. Eventually, discharges in the MWPC were breaking wires in DC1. These factors, particularly the threat to DC1 wires, led to the shutdown of the MWPC early in the run and before data acquisition.

After the 1990 LAMPF beam run, a modification to the MWPC was tested where the cathode foils were grounded and the wire anode plane was biased to a

positive high voltage, the converse of the initial configuration where the wires were grounded and the cathode foils biased to a negative high voltage. The scintillators with a cosmic ray trigger were used once again. While all scintillators were used in the trigger, only the lower quarter of the MWPC, 45° either side of the nadir, was used for this study. As before, the scintillators were assumed 100% efficient and the absence of an MWPC hit adjacent to a scintillator hit was counted as an inefficiency. The voltage was varied between 1650 volts and 1900 volts, where stability became problematic. The MWPC section was found to be more stable for the duration of testing. Some discharges occurred but were less frequent and did not result in broken wires. The efficiency obtained at various voltages is shown in figure 20. For both field on and field off measurements, plateau occurred at ~ 1850 volts.

The chamber clearly displayed much more reliable and stable behavior for this alternate scheme. Remaining problems such as wire to foil discharges and instability above 1900 volts were thought to be due to nonuniformities in the rohacell cylinder surfaces as mentioned before. A new initiative to replace the rohacell cylinders with more rigid and precise carbon fiber composite cylinders has been underway since early 1991. Initial cylinders constructed at the University of Houston have shown this approach to be a promising one with precisions in radius of $\pm 125\mu\text{m}$ and better attained.

III.5.3 Drift Chambers

The drift chamber (DC) array consists of three layered DC's. Until 1988 the design consisted of three individual DC layers, each consisting of inner and outer

Figure 20. MWPC Efficiency : Alternate Charging Scheme

cathode foils with an anode wire plane at the midpoint of the cathode planes. This required three additional rohacell cylinders, each supporting the outer foil of a given DC layer and the inner foil of the next DC layer. This design was found to be rather unstable primarily due to rohacell cylinder nonuniformities as discussed previously. After the 1988 test run at LAMPF, a new design was developed replacing the conventional design used until then. The final design is shown in figure 11. The original design of alternating sense and field wires for the anode planes was kept while the cathode foils were replaced by field wire planes. This design was found to be much more stable and reliable during subsequent in beam tests at LAMPF and so was adopted for all photon detector layers.

All field wires are 102 μm diameter gold-plated beryllium-copper while the DC1 and DC2 sense wires, intended to supply Z coordinate information, are 25 μm diameter stableohm resistive wires. The DC3 wires are 33 μm diameter gold plated tungsten wires. DC wires were installed as described above for the MWPC sense wires. Field wires were stretched prior to crimping with a 250 g mass. The resistive wires were to be used to obtain Z information through charge division ADC readout. Unfortunately, the ADC modules purchased by MEGA for this purpose were not yet available. One partially functional ADC module was available but was only suitable for test purposes. A charge calibration curve for one wire, obtained in 1990, is shown in figure 21. A 57%-43% argon-ethane gas mixture was used. This mixture was used due to its stability. It also provides a plateau typically over 100 V wide.

The Z-readout scheme described above was unreliable. The stableohm wires used were rather brittle and very prone to breakage as a result of foil to wire discharges. This was a problem particularly for the DC1 wires, being closest to the inner DC foil. An alternate scheme using delay lines etched into the cathode foil below DC1 has been tested and adopted following the 1990 run. A section of the etched foil is shown in figure 22. Each sense wire has two delay lines beneath it, one on each side of the cathode foil. The traces are offset by half a period so that only the long sections of the lines overlap. When a charge avalanche occurs at the sense wire, an image charge is induced in the trace on top of the foil, inducing an opposite charge on the bottom trace. Signals are transmitted to both ends of this transmission line and the time difference between the two ends determines the position of the avalanche. The half

Figure 21. Charge Collection for a Resistive Wire

period shift between top and bottom traces greatly increases the inductance of the line. This results in reduced signal transmission velocity and increased impedance leading to an improved signal-to-noise ratio. Bench testing has indicated successful operation of delay lines with charge collection in the particular cell of ~ 4 pC with an efficiency of better than 99% relative to the sense wire. Further bench testing has indicated a resolution of 5 mm FWHM for the central 80 cm of the full 174 cm length to be used. Resolution outside of this region worsens to 8 mm FWHM at the ends due to signal degradation in the delay lines. For the $\mu \rightarrow e\gamma$ measurement, we will

Figure 22. Delay Line Section

look at showers at dip angles between 10° and 45° . For the inner photon detector layer used in 1990, this puts all showers within the 5 mm resolution region.

During setup and testing at LAMPF in 1990 prior to beam availability, plateau curves were obtained for all 3 DC's. To maintain a uniform field profile in the DC's, field wires directly above and below each DC sense wire and those directly to the left and right of each sense wire are maintained at a given voltage, referred to as v_{low} . The remaining field wires are the four around each cell positioned diagonally to the sense wire. These wires are maintained at a 10% higher voltage, v_{high} , thus maintaining a uniform field profile throughout the drift cell. The foil below DC1 was maintained at a bias of 100 V lower than v_{low} . The plateau curves were obtained exactly as described for the MWPC. Once again, only the very top and bottom sections of the chambers were used assuming 100% scintillator efficiency. The resulting plateau curve

obtained for DC2 is shown in figure 23. Plateau curves for DC1 and DC3 are similar. Plateaus in the DC's occur at between 1750 and 1850 volts and are all more than 200 volts wide.

Figure 23. DC2 Plateau Curve

The signals are read out of both ends of the resistive wires of DC1 and DC2 and one end of the DC3 sense wires. A flow diagram of the electronics for the drift chambers and the MWPC are shown in figure 15. The signals are routed to the moon-plates and then to individual preamplifier circuits mounted on the motherboards. The preamplifier used is the same as for the MWPC and is shown in figure 16. For DC3

the preamplifier outputs are routed via RG-174 cables to the upper circuit of figure 17 and then to TDC modules in the fastbus system. For the resistive wires of DC1 the output of the preamplifier circuits is routed via RG-174 cables to the shaping amplifier circuits shown in figure 24. The circuit in the lower half of figure 24 is to used accommodate the the negative polarity signals input to the circuit after summing. The shaping amplifier outputs from either end of the wire are summed prior to being input to the amplifier-discriminator. Since the shaping amplifier inverts the signals, they are routed to the amplifier-discriminator circuit shown in the lower half of figure 17 and then to a TDC module. The ADC output of figure 24 is routed to a fan-in circuit for multiplexing into the few ADC modules available. Because of the limited supply and quality of ADC modules in 1990, this multiplexing was not done. The DC2 and DC3 amplifier-discriminator digital outputs are also routed to a multiplexing box prior to being fed into the second stage trigger module.

The drift chambers were also tested using the alternate biasing scheme as in the MWPC case. Again, the lower quarter of the drift chambers was used. The foil below DC1 and the field wires directly to either side and directly above and below were grounded in this case while the corner field wires were biased to -150 volts. The sense wires were biased to +1950 volts. Stability and efficiency of the drift chambers was unchanged while current mode did not occur until above 2100 volts, well above plateau voltage.

III.5.4 Photon Scintillators

Timing of the photon detector, and ultimately the entire experiment, is accomplished through the use of a layer of plastic scintillators. It is the innermost section

Figure 24. Shaping Amplifier Circuit

of the photon detector, as shown in figures 3 and 11, and is comprised of 40 separate scintillator bars, each measuring ~ 5 cm x 1 cm x 180 cm, with the 1 cm edges tapered 4.5° so that the individual scintillators form a cylinder when assembled. The scintillators, Bicron [37] type BC412, are polyvinyltoluene ($CH_{1.1}$). The granularity is necessary due to the rates we expect in the detector. The meantimer rates measured per scintillator during 1990 were typically 13 kHz time averaged and 200 kHz instantaneous during a beam burst.

The scintillators extend lengthwise along the z direction parallel to the beam direction. Scintillators are coupled to a phototube at each end via a 3 m long fiberoptic light guide. This light guide is "S" shaped with a sharp bend near each end, a

90° bend on one end to convey the optical signal radially outward from the scintillator and a bend of up to 90° to couple to the PMT. The fiberoptic material used is Mitsubishi Rayon EK80, consisting of 2mm diameter individual polymethylmethacrylate fibers with an index of refraction of 1.495, surrounded by a 21 μm fluorinated polymer cladding layer with index of refraction 1.402. The cladding material limits the acceptance cone of the fibers to $\pm 31^\circ$. Each light guide consists of 108 optical fibers bundled together into a single 'rope'. During fabrication, one end of the fiber bundle is glued into an injection molded plastic endpiece. After the glue has set, the fibers are milled off flush with the end piece, and the entire length of fibers is dipped lengthwise into a distilled water bath kept at 80 – 90° C so as to relax any kinks or bends in the fibers. The light guide is then wrapped along its length in black/grey shrink tubing for light sealing and glued into another endpiece. The shrink tubing also provides rigidity to maintain the shape necessary to convey the signal from the scintillator within the magnet to the PMT located outside the magnet. After the other end is milled flush with the plastic endpiece, lucite optical windows are glued to both ends of the light guide with Bicon BC600 optical epoxy. The injection molded endpieces are designed to couple, in one case, to the PMT, and in the other case, to the end of the scintillator. Coupling is made by an air gap. Bench tests in 1987 showed an appreciable ($\sim 80\%$) light loss at the coupling of the scintillator to the light guide due to the poor match between the scintillator bar and the acceptance of the fibers. Further bench tests were performed in 1989 to investigate the feasibility of soft plastic 'cookies' being inserted between scintillator and light guide to eliminate light

After transmission from the scintillator through the light guide the signal is read out by a Hamamatsu model R1355 photomultiplier tube. A block diagram for 1 complete scintillator channel is shown in figure 25. The PMT base circuit, a simple voltage divider, is shown in figure 26. The photomultiplier tubes require an environment free of magnetic fields to operate. They are located outside of the magnet in a region where magnetic field strength varies from 200-800 Gauss. The PMT for each channel is coupled to a light guide within a soft iron tube to provide gross magnetic shielding. Each PMT is placed within a thin μ -metal tube within the soft iron tube to shield against any remaining fields. The shielded PMT assembly is aligned perpendicular to the magnetic field lines to provide maximum shielding. Pulse height tests were performed at LAMPF in 1987 to evaluate the effectiveness of this shielding. A PMT placed in the above shielding was exposed to a ^{207}Bi source while the magnetic field was increased from zero to its maximum attainable field of 16.9 kG. No measurable difference between field off PMT signals and maximum field signals was observed.

The light remaining after transmission down the scintillator, through the light guide, and into the PMT produces a signal which is sent via a 47 ft RG-58 cable to a Dual Threshold Discriminator (DTD). A circuit diagram of the DTD is shown in figure 27. The upper portion of figure 27 is a transistor stage to produce an analog signal to correct the timing for slew caused by pulse height differences. The lower portion of the figure is a dual threshold discriminator which produces a digital output signal. The analog signal is input to a linear fan-in circuit shown in figure 28 to be

NOTE: UNLESS SPECIFIED, ALL RESISTORS ARE 100K 1/2W.

Figure 26. PMT Base Circuit Diagram

used for multiplexing the signal by a factor of 2 or 3 in layer 1, 4 in layer 2 and 5 in layer 3. The output signal is then sent via 100-ohm individual shielded twisted pair cables to the acquisition area in the MEGA counting house. It was to be input to a Phillips ADC module, but due to the shortage of such modules, this was not done for the summer 1990 development run at LAMPF except for brief tests of the linear fan-in module. The digital signal is sent, via flat twisted pair cable, to a logic fan-in circuit. This fan-in circuit is used for multiplexing the detector layer by the factor specified. The logic fan-in circuit is shown in figure 29. Because of the availability of electronics and the absence of additional photon detector layers during the summer 1990 run, signals input to the fan-ins were multiplexed by a factor of 1.

The resulting logic signal was then sent via flat twisted pair cable to the MEGA data acquisition area and into a Phillips TDC module. The DTD logic output is also

Figure 28. Linear Fan-In Circuit Diagram

NOTE: STARRED 100 OHM RESISTOR
REMOVED FOR UNUSED INPUT
CHANNELS

Figure 29. Logic Fan-In Circuit Diagram

Figure 30. Examples of ADC and TDC Spectra

that the ADC pulse height spectrum is dominated by Landau broadening rather than photostatistics. For the proton beam component, $\beta = .45$, resulting in a pulse height spectrum dominated by photostatistics with negligible Landau contribution. We therefore use the photostatistics dominated proton spectra to estimate the number of photoelectrons that we expect from the minimum ionizing positrons and electrons that predominate during actual data taking. We do this by scaling the number of photoelectrons produced by the proton beam component by the ratio of ADC pulse heights of both beam components.

Figure 31. Setup for the 1987 LAMPF Run

The beam was focused normal to the scintillator bar. Data were taken at 5 positions along the 180 cm length of the scintillator. ADC and TDC spectra are shown in figure 32 for $z=107$ cm.

The attenuation length was determined by least squares fitting the ADC pulse height spectra centroids to an exponential $A = A_0 e^{-\frac{z}{\lambda}}$ where A is the pulse height and λ is the attenuation length. The data used in the fits is shown in figure 33. The attenuation length obtained was 268 ± 97 cm, which is a weighted average of 4 values.

The timing resolution of the detector was measured by looking at the Full Width at Half Maximum (FWHM) of the TDC peak of the pion component at the positions specified. The FWHM was measured in the TDC spectra from both ends of the

Figure 32. Sample ADC and TDC Spectra

detector and added in inverse quadrature as $\frac{1}{(\delta)^2} = \frac{1}{(\delta_{Left})^2} + \frac{1}{(\delta_{Right})^2}$. The timing resolution was thus measured as ~ 800 ps, averaged over the 5 positions indicated in table 4.

The number of photoelectrons produced by the particle passage and propagated to both PMT's was calculated as $N = \left(\frac{A_P}{\sigma_P}\right)^2 \left(\frac{A_\pi}{A_P}\right)$. Results are shown in figure 34 for numbers of photoelectrons observed out of either end of the scintillator bar, as well as the total observed from both ends. This number includes the 80% reduction in light at the scintillator light guide interface and the efficiency of the PMT. Simple interpolation to the far ends of the scintillator at $z=0$ and 178 cm indicates that a

Figure 33. Attenuation Length Data

minimum of ~ 20 photoelectrons will be observed at one end of the scintillator for a minimum ionizing particle traversing the scintillator at the far end, while a total of ~ 73 photoelectrons will be observed out of both ends. Propagation velocity was determined by doing a linear least squares fit on the TDC time difference spectrum between the left and right end TDC signals versus the difference in propagation distance for left versus right travelling signals. The results are shown in figure 35 and the propagation velocity thus found was $17.67 \pm .68 \text{ cm/ns}$.

Table 4. Timing Resolution Measurements - Pions

RUN	Z	δ_L	δ_R	δT
100	43.2cm	22	26	809ps
101	144.	26	22	821
102	107.	24	24	793
103	67.3	23	27	832
104	26.0	20	27	787

δ_L, δ_R given in units of TDC channels
1 channel=50ps

Figure 34. Photoelectrons Observed

Figure 35. Propagation Velocity Data Used

III.6 The Trigger and Data Acquisition Systems

Figure 36 shows the integrated trigger and data acquisition system. All experimental data is directed into the FastBus (FB) system containing ADC's, TDC's, and other modules. The Fastbus system is controlled by the General Purpose Master (GPM), later updated by the improved Cern Host Interface (CHI). The GPM consists primarily of a 68000 processor running at 16 MHz. The first stage trigger module consists of ECL Programmable Array Logic (PAL) chips. The second stage trigger module consists of CMOS Erasable Programmable Logic Device (EPLD) chips. These chips are programmable to the specific trigger conditions required by MEGA.

Figure 36. Trigger and Data Acquisition Setup

The first stage trigger receives the photon scintillator and MWPC signals. Each photon scintillator input signal is a meantime of the upstream and downstream signals of each scintillator channel. Each MWPC input signal is a "cluster" of 4 contiguous cells. The trigger logic searches for specific patterns signifying a desired energy range or location of a given shower. The principal patterns sought by the first stage trigger are:

1. at least three MWPC cluster hits 9-13 wide with at least two accompanying scintillator hits;
2. at least three MWPC cluster hits 3-13 wide with at least two accompanying scintillator hits;

3. at least three non-adjacent scintillator hits 4-6 wide;
4. at least one hit in upper scintillator hemicylinder;
5. at least one hit in lower scintillator hemicylinder;
6. OR of all scintillators in a given photon detector layer;
7. "back-to-back" showers obeying conditions 1 or 3 above;
8. "back-to-five-fold" showers obeying conditions 1 or 3 above;
9. various logical signals signifying locations of the above
patterns. (upper, lower, left or right hemicylinder)

The first two patterns require the MWPC and were not used in 1990. The first results in a transverse momentum cut at ~ 35 MeV/c while the second leads to a lower cut at ~ 10 MeV/c. The third pattern requires swapping logic chips in the trigger module and was necessary to take muon data in the absence of the MWPC. It leads to a transverse momentum cut of ~ 30 MeV/c. The fourth and fifth patterns lead to a cosmic ray trigger, requiring the cosmic ray particle to hit both upper and lower halves of the detector. The sixth trigger condition is used for timing and diagnostic purposes. The two "back-to-back" triggers are used for pion data acquisition. The last condition is used for the generation of various triggers in the routing box for diagnostic and user specified purposes.

The routing box receives the information from the first stage trigger box along with other input signals from the electron scintillators, ring counter and IBV counters

Table 5. Routing Box Trigger Conditions.

1. High Energy Gamma
2. Low Energy Gamma
3. Cosmic Ray
4. Photon Scint • Ring Counter
5. Ring Counter
6. Electron Scintillator
7. Pulser to Electron and Photon Gates
8. Back to Back Gamma
9. Back to Five Fold Gamma
10. Low Energy Gamma • IBV
11. High Energy Gamma • Electron Scintillator
12. High Energy Gamma(up) • Low Energy Gamma(down)
13. High Energy Gamma(down) • Low Energy Gamma(up)
14. Low Energy Gamma (up and down)
15. High Energy Gamma (up and down)

to logically detect more complicated, user specified trigger conditions. The available trigger conditions are listed in table 5.

The trigger conditions utilized for photon detector setup, testing and operation in the summer 1990 run were 1, 3, 4 and 9 in the table. For triggering purposes, the photon scintillators were given a common time base relative to the ring counter using an oscilloscope. To time the photon scintillators more precisely and for software purposes the ring counter AND photon scintillator trigger was used. Muons stopped in the magnet entrance window emit positrons. If the magnet is off, some of these positrons will pass through the ring counter, through the electron scintillators and finally through the photon scintillators. If the magnet is on, some positrons pass through the ring counter and then orbit back into the Pb annulus beneath the electron scintillators. The positrons stop there, producing photons through bremsstrahlung

or annihilation with bound electrons. Some of these photons pass through the photon scintillators. The ring counter AND photon scintillator trigger thus provides a common time base to calibrate all scintillators for both magnet on and off conditions. This trigger was also used to study magnet on TDC time drifts as measured at roughly 8 hour intervals over several weeks. The cosmic ray trigger, requiring at least one scintillator firing in the upper hemicylinder and at least one in the lower hemicylinder, was also used for evaluation and testing as well as calibration and was useful for on line monitoring of detector function during data acquisition. The cosmic ray trigger was also utilized to monitor variations in various experiment signals. The high energy gamma trigger, requiring three non-adjacent scintillator hits 4-6 wide, was used for acquiring inner bremsstrahlung data. The "back to back" trigger required a high energy gamma trigger with a similar trigger $180^\circ \pm 30^\circ$ from the first. The "back to five fold trigger", used for pion data acquisition, required a high energy trigger with a similar trigger in the quadrant opposite the first. This was useful for pion data acquisition. When a π^- stops within the target, it is captured at rest by a proton in the nucleus. The π^0 is then emitted by the interaction $\pi^- p \rightarrow \pi^0 n$ with ~ 3 MeV of kinetic energy. The π^0 then decays via $\pi^0 \rightarrow \gamma\gamma$ in $\sim 10^{-16}$ sec, resulting in the photons being emitted at less than 180° from each other.

The routing box is initialized at the beginning of a given run to search for one or more of the triggers of table 5. When a first stage trigger is generated, the routing box is notified. If the system is busy collecting another event, the trigger is ignored. If not, the routing box triggers all modules, including ADC, TDC and latch modules to start collecting their particular data. Simultaneously, the routing box signals the

second stage trigger to evaluate the photon drift chamber signals. This stage of the trigger evaluates hit patterns in the drift chambers, and requires the following: the shower must consist of at least three non-adjacent hits between 14 and 24 cells wide in DC 2, the shower must be at least 10 cells wide in DC 3, and each wire cell hit in DC 3 must be correlated with, at most one cell distant from, a hit in DC 2. While the first stage trigger used in 1990 suppresses showers with energies less than about 30 MeV, the second stage trigger also suppresses much of the background contained in the DC's which will pass the first stage trigger. The second stage trigger then sends a signal back to the routing box depending on what it found. If the second stage trigger passes the event it notifies the routing box and all latch modules are signalled by the routing box to save their data. The ADC and TDC modules will passively save all data unless notified otherwise. If the event fails the trigger, the routing box sends a fast clear signal to all ADC and TDC modules. These modules then dump their data from this event and wait for the next data collection signal from the routing box.

When a user specified number of events have been collected successfully, a GPM trigger is generated. This trigger notifies the GPM to have each crate of up to 22 individual modules dump all their data to the GPM to be built into a megablock. When all modules are dumped they are combined into a GPM cluster headed by a GPM block containing information such as run number, time, date and macropulse number. For the 1990 LAMPF run, most of the GPM clusters consisted of eight megablocks, each containing 5 individual triggers.

When a given GPM cluster is completed, it is transferred to an Advanced Computer Project (ACP) node. These ACP processors proceed to digest the GPM cluster,

checking each event for conditions specific to $\mu \rightarrow e\gamma$ candidate events within the precision of the experiment. The ACP performs more sophisticated calculations allowing it to make more precise cuts on the energies of the photon and positron components of the decay, their relative timing and their relative direction. As described earlier, their energies should be 52.8 MeV each, their timing coincident and their directions back-to-back. The ACP then transmits candidate events to the Microvax III where they are relayed to a particular storage medium, either disk or tape.

During the summer 1990 run at LAMPF, Inner Bremsstrahlung data was obtained without either the second stage trigger box or the ACP. The second stage trigger box was suffering hardware problems and the ACP software was being debugged. Inner bremsstrahlung data is easily filtered offline and is described further in the next chapter. $\mu \rightarrow e\gamma$ data acquisition proceeded precisely as detailed above.

CHAPTER IV

EXPERIMENTAL DATA ANALYSIS

Data was acquired for the testing and evaluation of the photon detector system at LAMPF in the fall of 1990. Analysis of this data was performed on a DECstation 5000-200 running ULTRIX 4.2 and utilizing FORTRAN as the primary programming language. The two primary pieces of software utilized are the 30,000+ line experimental analysis code and a several thousand line Monte Carlo simulation code, both originally written and maintained on a VAX system.

Three types of data were taken: cosmic ray events, muon inner bremsstrahlung (IB) data, and pion data. The cosmic ray data was used to obtain drift time versus drift distance calibrations for drift chamber cells. It was also used to measure chamber efficiencies and obtain plateau measurements. The inner bremsstrahlung data provided us a number of showers to analyze. They were used to determine and evaluate various cuts and filters to eliminate events because of noise, background or energy cuts. The analysis was done in parallel with Monte Carlo simulations of the detector geometry. These comparisons, including single event displays, were instrumental in developing much of the filtering and fitting algorithms. Because the resistive wire readout for z determination and the MWPC were not operational during data acquisition, the pion data could not be used, as the vertex of a pion event is almost indistinguishable from other tracks in the dc's without MWPC and Z information.

The remainder of this chapter contains a discussion of software used, followed by a detailed analysis of various calibrations and cuts to be applied to the IB data.

The analysis software is then evaluated in detail, resulting in an IB perpendicular momentum spectrum.

IV.1 Analysis Software

IV.1.1 Experimental Data

The analysis code consists of three principal parts: the primary analysis section which reads in individual events and deciphers and relays the information to the appropriate data arrays, the secondary analysis section which consists mainly of user written subroutines which process data from primary analysis data arrays according to user specified needs to do real physics calculations, and graphical display of both histograms and single events anywhere within the MEGA detector system. The code also offers the user the option of building a local replay image using user rewritten versions of any replay subroutines rather than system global versions. This makes the analysis code very versatile and adaptable to a variety of user specific needs.

The code was written for both on-line and off-line analysis on a VAX system and was ported to the DECstation [38] for off-line analysis only. The original code contained numerous calls to DEC VAX VMS system functions, as well as CERNLIB [39] and Q [40] routines and Template [41] graphical display routines. In porting the code to the DECstation, the VMS system calls and the Q routines used were replaced with rewritten equivalents. The CERNLIB routines were available for the DECstation. The Template calls were used for Single Event graphical Display (SED). These subprogram calls were common in SED, making porting to ULTRIX prohibitive. The photon arm portion of the SED code was rewritten for the DECstation using the

DEC GKS-3D graphics libraries. Template was later purchased for the DECstation and will make eventual porting of SED to the DECstation possible.

IV.1.2 Monte Carlo Simulation

The photon detector Monte Carlo code utilizes the EGS4[35] code system to simulate photon detector response. EGS4 is a sophisticated Monte Carlo subroutine package allowing the user to specify both detailed detector geometry and environment and initial particle properties as well as the complexity of the simulation. The user defines the geometry as well as various simulation parameters including incident particle parameters and energy cutoffs at which EGS4 may discard a given primary or secondary (or tertiary ...) particle. The Monte Carlo code, written in FORTRAN, was ported to the DECstation with little effort. It consists of event generation, trigger simulation and analysis sections. In previous years it has been instrumental in evaluating detector design options. It is used here in parallel with analysis of real data to evaluate detector performance and develop analysis software. Detector response is smeared according to various energy, position and timing resolution values. The smearing values used are obtained from well known characteristics of an argon-ethane gas mixture. Smearing values used include uncertainties in energy deposition in a drift cell, discriminator thresholds, discriminator timing slew and drift time resolution.

The Monte Carlo code also includes background noise as studied in 1989 at LAMPF. The 1989 data from the same detector was analyzed to look for noise in the scintillators and the drift chambers. The data was acquired using a pulser (pass all) trigger. The scintillators were scanned for single or correlated double hits and appropriate probabilities assigned for each type of occurrence. The drift chambers

were scanned for clusters of contiguous hits of widths one, two, or three. The drift chambers were also scanned for "stacks" of hits one, two, or three drift cells in height. Appropriate probabilities were also assigned. The probabilities are scaled from full (6.0) beam intensity according to a Poisson distribution derived by repeating the above for several intensities.

IV.2 Drift Response Calibration

The x-y position of a particle's passage through a drift chamber cell is determined through measuring drift distance to the sense wire. Fits to these hit locations determine the perpendicular momentum of the converted photon. It is therefore necessary to calibrate the drift chamber wire cells to correct for drift distance from the actual hit location in a given drift cell to the wire itself. This is accomplished by using cosmic ray data with the magnetic field on to simulate $\vec{E} \times \vec{B}$ drift profiles for muon data acquisition as closely as possible. For this purpose, we use a series of runs consisting of 617,000 cosmic ray triggers. Cosmic ray flux varies approximately as $\cos^2\theta$, θ measured from the vertical. We therefore use the 20 cells located contiguously at the top of the detector, 10 to the left of the vertical and 10 to the right of the vertical. These cells are all within 18° of the vertical so that all 20 cells are approximately uniformly illuminated by cosmic rays over the course of the acquisition of this data. We may use the equivalent 20 cells across the bottom of the detector. The calibration should be the same as for the top 20 wires except for a common time shift corresponding to the propagation time of a typical cosmic ray from the top to

Figure 37. Multiplicity Spectrum: Cosmic Ray Calibration Data

the bottom of the detector. The 20 wires at the top of the detector should supply adequate statistics and an adequate sampling of drift cells to obtain the calibration.

We apply multiplicity constraints to the data used, multiplicity being the number of cells hit in a given drift chamber for the 20 wires in question (#42-61). To account for edge effects we will also include wires 41 and 62 when counting multiplicities involving wires 42 and 61 respectively. Since cosmic rays are typically of high energy they should display little curvature as they traverse the detector, so that most events should be of multiplicity one for a given DC. For a uniform flux of cosmic rays across a given cell, we expect a few cosmic rays to traverse the cell near the boundary of two adjoining cells, thus causing both cells to be hit. Clearly, any

Figure 38. TDC Spectrum, DC1 Wire 51

multiplicity three or greater events can not be from a simple cosmic ray event, and imply electronic noise or a secondary process such as an electron scattered out of the Pb converter by a cosmic ray shower. To assure that we have only fairly clean events for the calibration, we restrict the data used for calibration to multiplicity one, as well as multiplicity two if the two hits are adjacent. Figure 37 shows the multiplicity spectrum for the specified data for DC1. Of the 617,000 triggers, $\sim 156,000$ fell within the 20 wire calibration region, $\sim 150,000$ being of multiplicity one or multiplicity two with the hit wires adjacent to each other. The resulting TDC spectrum of wire 51 in DC1, located in the center of the 20 wires, is shown in figure 38, and the integrated TDC spectrum, a drift time versus drift distance curve, is shown in figure 39.

Figure 39. Integrated TDC Spectrum, DC1 Wire 51

We use the integrated spectrum to calibrate this drift cell. The TDC module used to obtain the spectrum of figure 38 was calibrated to 800 ps per channel. If we assume uniform illumination of the entire drift cell then each channel also corresponds to a common fixed drift distance dx . Each channel of the integrated TDC spectrum therefore corresponds to the total drift distance Σdx of the charge from a given location within the drift cell to the sense wire.

The initial part of the spectrum of figure 39 is not linear as one would expect. This is because of differences in pulse heights of the signals within a given drift cell caused by statistical differences in charge creation and collection near the sense wire. Because of this, the leading edge of the pulse, which is amplitude dependent and

provides the stop signal for the TDC module, will vary by as much as 10 ns between pulses. This causes the initial part of the integrated TDC spectrum to be nonlinear as shown in figure 40. To correct for leading edge effects, a program was written that scans the spectrum beginning at channel 0. When 1% of the maximum frequency is reached to assure that the code has located the initial leading edge part of the spectrum the code skips 20 channels. This takes us beyond the leading edge part and into a fairly linear section of the spectrum. The code then does a linear fit to the next 25 channels. It replaces the leading edge part below the fitted 25 channels with an extrapolated line. This line has the same slope as the fitted line and is projected down to the x-axis. This x-intercept value corresponds to a direct hit on the wire. Any drift times having values below this are considered direct hits. The resultant extrapolation is shown as the dashed curve in figure 40.

The TDC spectra for individual drift cells differ due to differences in electronic and cable transmission times. We correct for this by translating each integrated TDC spectrum so that the intersection of the leading-edge corrected spectrum with the x-axis is at channel zero. Then channel zero corresponds to zero drift time for all spectra. All integrated TDC spectra are normalized so that they all have the same value at channel 500, where the spectrum reaches its maximum, so that we may compare spectra. Figure 41 shows the resulting integrated TDC spectrum for DC1 wire 51.

It is clear from figure 41 that most of the particle drift in a given drift cell occurs over a 300 channel region beginning at t_0 , as the spectrum is to 98% of its

Figure 40. Integrated TDC Spectrum; Wire 51

maximum by channel 300. The TDC modules we use are calibrated to 800 ps per channel indicating a maximum drift time of 240 μsec over 300 channels. The extremes of the ordinate of figure 41 correspond to the extremes of the drift cell. The minimum values correspond to direct, or nearly direct, hits on the sense wire at the cell's center. The maximum values of the ordinate correspond to particle drifts from the furthest extents of the cell, either to the left or right of the sense wire. Drift times beyond the 300 channel calibration region are mostly due to cross talk from adjacent cells. When a particle passes near a cell boundary, the magnetic field profile in that region may cause charge to drift across the cell boundary into the adjacent cell and eventually

2 of 2

Figure 41. Corrected, Normalized Integrated TDC Spectrum; DC1 Wire 51

into the adjacent sense wire. This will, apart from omitting a legitimate DC hit, generate a false hit in the adjacent cell with a relatively long drift time.

Figure 42 shows the resulting normalized integrated TDC spectra for all drift cells in DC1, excluding 3 missing wires. Because of nonuniformities in the MWPC cathode foils, particularly the foil directly below DC1, and other electronic problems, some sense wires in these 20 cell spans did not survive installation and testing. Since the drift profiles of directly adjoining cells in the same DC layer are radically different from that of a typical drift cell, we eliminate all such cells from the calibration. This can be seen in figure 42, where the four drift time versus distance curves to the right of the others are for the cells adjoining missing wires. The two cells located directly

above and below a dead cell and the four cells located diagonally to a dead cell were found to have drift profiles similar to those not adjacent to dead cells, indicating little effect due to nearby dead drift cells. This leaves only 13 wires for DC1 in the span of 20, while not affecting DC2 or DC3.

In figure 42, the maximum variation in drift distance determination between curves, excluding the four cells adjacent to missing wires, is 20000, or $\sim 10\%$ of the full scale of 200,000. For a DC1 cell width of .53 cm, this variation is .53 mm. We select a single calibration for DC1 by averaging over all curves excluding those adjacent to dead wires. The maximum error in drift time if we use this average curve to determine drift times of all DC1 cells is therefore $\pm .27$ mm, or a sigma of $\sim .23$ mm. Repeating this process for DC2 and DC3, we similarly obtain separate average calibration curves with corresponding maximum errors of $\pm .20$ mm for DC2 and $\pm .18$ mm for DC3 corresponding to sigmas of .17 mm and .15 mm respectively. The equivalent drift profiles for DC2 are shown in figure 43. The improvement in the absence of dead drift cells and not being in close proximity to the DC1 foil is clear.

To obtain values of t_0 for all wires, we may not use cosmic ray data as above because the cosmic ray trigger does not utilize the four scintillators along the horizontal, thus allowing only accidentals for use in obtaining t_0 values for the 20 wires adjacent to these 4 scintillators. Also, the $\cos^2\theta$ nature of cosmic rays and the trigger requirement of a scintillator hit in the upper half of the detector coincident with one in the lower half leads to fewer triggers in wires away from the very top region, or very bottom region, of the detector. Also, the cosmic ray trigger has a different generation

Figure 42. Integrated, Normalized Drift Spectra; DC1

time than the HI- E_γ trigger. To obtain t_0 values for use in analyzing electromagnetic showers, we therefore use IB data taken using the HI-E γ trigger. This supplies a uniform illumination of all drift cells. To obtain sufficient statistics and therefore minimum least squares fitting errors in obtaining t_0 values, we use all available IB data, resulting in errors in t_0 values of roughly 1 channel, or less than 1 ns. These errors are obtained assuming linearity of the spectra in the absence of leading edge effects.

Since the DC1 and DC2 sense wires were read out from both ends and later summed at the input to the amp-discriminator cards, it may be necessary to correct the t_0 values for these wires as a function of z-position of the hit along the wire. Let

Figure 43. Drift Spectra; DC2

us consider four separate cases, each case for a hit in a particular quarter of the 180 cm wire. These translate to signals that, on average, originate from $z=\pm 23$ cm and $z=\pm 67$ cm. For a signal velocity of $\pm 0.9c$ in the wire, and assuming that the amp-discriminator card will fire on arrival of the first and stronger signal, the four signal types should arrive at two separate times. The two nearer the middle of the wire should arrive ~ 2 ns later than the two nearer the end. For DC3, wires are read out from one end only. DC3 may thus experience larger variations in propagation times.

To see if this effect is noticeable and thus necessitates t_0 corrections, we need z -information for the four hit types listed above. We obtain z -information by writing a replay analysis routine which uses the scintillator TDC times. The scintillators are

Figure 44. Typical Scintillator TDC Time Difference Spectrum. This Spectrum May be Used as Rough ($\sigma=\pm 6.6$ cm) Z-Calibration.

calibrated by taking the difference of TDC times from both ends, which is proportional to z , for each scintillator for 100,000 cosmic ray triggers. A time difference spectrum is shown in figure 44. Assuming linearity, the extremes of this spectrum correspond to z -values of ± 90 cm and provide us with a simple linear calibration. The errors involved in determining z in this fashion were determined by taking a brief magnet off run. The trigger was an any-gamma trigger with the available dwarves operating. In analyzing this data, a coincidence was required between an e^+ MWPC and a scintillator. For the e^+ MWPC hit, the positron was required to hit the MWPC twice, thus defining the straight-line trajectory of the positron. The trajectory was

then tracked to the appropriate scintillator, supplying a z -position of the scintillator hit independent of scintillator TDC times. The z -value obtained is accurate to less than 1 cm, depending only on dwarf cathode strips. We thus have a more accurate z -value for comparison to the value obtained using scintillator TDC values. For this purpose we selected an MWPC and scintillator that lined up with the target so as to maximize our statistics. We found that the z -positions thus obtained varied by 15.7 cm FWHM. This translates to a $\frac{2}{3}$ ns uncertainty in signal propagation time.

The data used to obtain t_0 values was subdivided into four groups as described above. The t_0 values obtained for the four groups were found to vary from one another by less than 1 ns, so that a correction for this effect is not justified. In future runs, when the detector has delay line z -readout, this effect may be investigated more thoroughly.

IV.3 Drift Time Cut

Figure 38 shows a typical TDC drift time spectrum. As we saw in the drift distance calibrations, drift times more than about 300 channels above t_0 are primarily due to charge drifting from adjacent cells. To eliminate these drift times we need to apply a drift time cut in the second stage filter code. To determine this cut, we measure wire efficiencies for various cuts around the value $t_0 + 300$. If the cut is too high, too many of the long drift time events are passed and contaminate legitimate events. If the cut is too low, too many legitimate DC hits are rejected, lowering the efficiencies of the wires and leading to the rejection of otherwise good events. The efficiency code we use looks at a cosmic ray run of 50,000 triggers taken immediately

Figure 45. DC1 Efficiency

after the inner bremsstrahlung data was acquired. The code scans the event for a "cluster" of 1 or 2 contiguous hits in DC2, occurring above an active scintillator, then scans DC3 for an adjacent cluster of one or two hit cells signifying a legitimate particle track. If such a cluster is found in DC3 nearby, then DC1 is similarly scanned. If a cluster is found, a DC1 efficiency is logged. If not, an inefficiency is logged. The analogous algorithm is applied to measure DC2 and DC3 efficiencies. Unless detailed particle tracking is done, it is difficult to determine exactly where the inefficiency has occurred, so we have divided the 208 wires in each DC into 13 groups of 16 wires each, exactly as the wire outputs are grouped electronically onto discriminator cards. When an inefficiency is found it is not logged if it occurs near a dead wire in the same

drift chamber. Figure 45 shows the results for DC1 for our run of 50,000 triggers for cuts ranging from $t_0 + 250$ to $t_0 + 450$ in 25 channel steps. In each case, two DC's were given a cut of $t_0 + 500$ (well above saturation), while efficiency was measured for the remaining DC for the range of cut values discussed above. Figure 45 shows the results for DC1 cards 2, 3, 10 and 11. These cards are located near the very top and bottom of the detector and, as discussed above, receive a uniform illumination across the entire card as well as more statistics for the cosmic ray trigger. DC2 and DC3 spectra are similar with maximum efficiencies of .97 and .99 respectively. Cuts of $t_0 + 300$ for DC1, $t_0 + 325$ for DC2 and $t_0 + 350$ for DC3 are indicated. A lower cut degrades efficiency, while we gain little efficiency for a higher cut.

IV.4 Monte Carlo Calibration

Monte Carlo calibration was accomplished by comparing real data to Monte Carlo data throughout the analysis and development of the analysis code. The discriminator thresholds were varied within the Monte Carlo trigger simulation so that the chamber efficiency matched that obtained in determining TDC cuts. The threshold was varied separately for each of the three DC's while the other two remained fixed. Next, the noise levels simulated in the Monte Carlo were set appropriate to a beam intensity of .22 of full intensity. This corresponds to our MS01 setting of 8.7 as seen in figure 5. Also, in the process of analysis, the chi-squared spectra were compared for real and Monte Carlo data. The real data chi-squared contained a significant shoulder not present in Monte Carlo data. This shoulder is primarily due to inter-cell

crosstalk effects and background from soft photons originating in the Pb annulus below the electron scintillators. An attempt to simulate this in Monte Carlo was done by smearing the data a second time, excluding noise and efficiency effects for the second smear. This procedure met with some success. The chi-squared distributions matched much more closely, though the shoulder in the real data spectrum was not entirely reproduced in the double smear Monte Carlo spectrum. More importantly, the perpendicular momentum spectra for Monte Carlo and real data matched more closely.

The analysis of the next chapter is done using this double-smear tactic for Monte Carlo events. A double smear implies $\sqrt{2}$ degradation in resolution and appropriate scaling of smearing parameters. These smearing parameters include energy resolution of ionization energy deposited in a given drift cell, discriminator thresholds for a given drift chamber layer (mentioned earlier), discriminator timing slew and time resolution. Initial values were determined through theoretical calculation, bench tests or in-beam tests. Fine tuning of the Monte Carlo at a higher level than is done here, however, is problematic. The quality of the photon arm data for 1990 is not sufficient to attempt an improved calibration. With an improved detector and several detector layers present, one can obtain much better cosmic ray data to determine drift distance versus drift time spectra. We assumed in our calibration that the electrons drifting to the sense wire follow a roughly circular spiral leading to circular equal drift time contours. In reality, $\vec{E} \times \vec{B}$ effects cause the equal drift time contours to be somewhat elliptical. With two photon detector layers present we may better track the curvature of the cosmic rays as they traverse the system. This added information should permit

us to resolve left-right ambiguities in cosmic ray events and better determine drift behavior.

IV.5 Muon Inner Bremsstrahlung Data

There were a number of dead DC cells due to missing wires. These dead cells, particularly when several occur within a single photon shower, can have adverse effects on the various filtering and fitting algorithms. Fortunately, nearly all of these dead cells, ten of twelve, occurred in half of the detector. We therefore perform the IB analysis and evaluation excluding DC wires #40-135. This effectively leaves the left half (55%) of the detector shown in figure 11, referred to as the clean half of the detector. It contains only two dead cells a reasonable distance apart, so that little contamination of particle tracks should occur. Further analysis indicates that 45% of showers that pass all filtering stages and are successfully fitted occur in the clean portion of the detector. We use these showers, discarding the other 55%, for our analysis. The showers not in the clean portion of the detector are noisy and were seen in SED to contribute significantly to filtering and fitting errors. Also, the Monte Carlo simulation does not include dead cells so any comparison between real and Monte Carlo data is much more reasonable using only the "clean" events.

IV.5.1 First Stage Trigger

We estimate the filtering rate of first stage trigger function using the HI- E_γ trigger during acquisition of IB data by using scalars that are recorded to tape periodically during any data acquisition. For this purpose and any further evaluations of filtering and fitting codes in this chapter, unless otherwise specified, we utilize an

IB run of $\sim 140,000$ triggers acquired roughly at the midpoint of data acquisition. This data subset, run 1200, comprises $\sim 11\%$ of the entire IB data set but provides sufficient statistics for the purpose at hand. All available IB data will be presented along with comparable Monte Carlo statistics in the results chapter. The improved statistics will also enable us to compare IB data to Monte Carlo for transverse momenta above 50 MeV where the inner Bremsstrahlung spectrum decreases rapidly to the endpoint at 52.8 MeV. The scalars obtained for run 1200 are listed in table 6.

Table 6. Run Scalars for Run 1200

Scalar#	Routing Box Signal	Occurrences
1	High E Gamma (1st Stage Trigger)	236267
10	High E Gamma Triggers (Less Busies)	139798
66	Beam Gates	408799
67	100 kHz Pulses	207508429
68	100 kHz Pulses•Beam Gates	15153006

For comparison, we produced an IB Monte Carlo data set. The data set was produced by throwing Inner Bremsstrahlung photons above 20 MeV through the detector geometry. 5,000,000 photons were thrown. This provides sufficient statistics for the various filtering and fitting stages of the analysis code. As was the case for run 1200, only the first stage trigger was simulated. The other triggers are simulated from the originally generated data set as needed for comparison to run 1200.

Scalar #66 is the number of beam pulses incident on the target while #67 is a measure of total time elapsed during the run, in this case 34.6 min, consistent

with log book entries. Scalar #68 is the AND of the previous two and is a measure of the integrated time for beam on target, 152 sec here. Scalars #1 and #10 of table 6 indicate a 40% deadtime. Scalar #10 over 152 seconds of beam on target indicates an incoming data rate from the first stage trigger of ~ 1 kHz. Since the second stage trigger and the ACP were not operational during IB data acquisition in 1990, the data acquisition rate was limited by the speed of the Microvax building GPM clusters, which was ~ 1 kHz in 1990. The ratio of these last two scalars gives a beam duty factor of 7.3%, also consistent with log book entries. During this run the beam slits were set to 8.7. Figure 5 indicates a beam flux of 4×10^6 muons incident on target per second (time averaged rate) for this slit setting. This indicates an integrated flux of 8.32×10^9 μ -stops during the run. Thus the overall filtering rate of muon decays including the IB branching ratio (1.4%), solid angle covered by the detector (0.77), converter and detector efficiencies and first stage filtering is 2.84×10^{-5} per μ -stop excluding deadtime. Deadtime lowers this to 1.68×10^{-5} per μ -stop. The Monte Carlo simulation of 5,000,000 μ -decay γ 's calculated a branching ratio for IB decay of 4.581×10^{-3} over the selected energy range indicating 1.092×10^9 μ -stops. The Monte Carlo run resulted in 24,594 photon showers passing the first stage trigger indicating a filtering rate of 2.25×10^{-5} , in reasonable agreement with the rate for run 1200. The difference is due to the presence of photons generated by positrons stopping in the Pb layers beneath the electron scintillators. These photons are not included in the Monte Carlo simulations. The perpendicular momentum spectrum of Monte Carlo events surviving the first stage filter is shown as the solid curve of

figure 46. The perpendicular momentum here, and henceforth, is defined as the total perpendicular momentum of the e^+e^- as the pair enters the drift chambers. It is obtained from the Monte Carlo history file. The first stage filter effectively eliminates those showers below $\sim 30\text{MeV}$. The dashed curve is for a Monte Carlo run assuming the MWPC is present. The first stage trigger requiring at least three MWPC cluster hits of a width between 9 and 13 cells with two accompanying scintillator hits, as discussed in the previous chapter, is used. The resulting perpendicular momentum spectrum of figure 46 shows a much sharper cut at $\sim 35\text{ MeV}/c$.

Figure 46. Perpendicular Momentum for Monte Carlo Showers Passing the First Stage Trigger. Solid Curve is for Scintillator Only Trigger. Dashed Curve is for Scintillator-MWPC Trigger.

IV.5.2 Second Stage Filter

While the first stage trigger succeeds in eliminating events below ~ 30 MeV, the second stage filter is designed primarily to eliminate background and noise in the photon chambers. This filter evaluates hit patterns in the drift chambers, and requires the following: the shower must be between 14 and 24 cells wide in DC 2, the shower must be at least 10 cells wide in DC 3, and each wire cell hit in DC 3 must be correlated with, at most one cell distant from, a hit in DC 2. Since the second stage trigger box was not operational during IB data acquisition, it is simulated in software. The various cuts applied by the second stage filter are shown in table 7 for run 1200 and Monte Carlo data. Multiplexing was enabled and data was multiplexed by a factor of 4 to properly simulate the on-line second stage trigger function. The cuts listed are applied in the order listed and the numbers are the percentage of showers eliminated by a particular cut. The final entry is the percentage of showers passing the second stage filter and prior to any additional filtering or fitting. The discrepancies in the filter rates are again primarily due to the soft photons originating in the Pb annulus beneath the electron scintillators. These background photons, generated by energetic Michel positrons stopping in the Pb, are not simulated in the Monte Carlo code. Work to integrate photon detector and positron detector Monte Carlo codes including this and other background sources is ongoing. Since both multiplexing and the second stage trigger were not operational in 1990, further evaluation of filtering

Table 7. Filtering Rates for the Hardware Second Stage Trigger Assuming Multiplexing Present: Real versus Monte Carlo

Reason For Failure	Monte Carlo	Run 1200
problem event (array overflow etc.)	0	0
too few dc2 hits	21.7	30.6
too few dc3 hits	3.9	5.2
too narrow in dc2	25.2	28.4
too narrow in dc3	2.9	2.6
pattern requirements failed	2.4	3.9
passed second stage filter	44.1	29.3

(all numbers in %)

and fitting will be done assuming no multiplexing.

The offline second stage filter we use for actual analysis is more refined than the hardware second stage filter used above. No multiplexing is done since none was done for data acquisition in 1990. The TDC cuts already mentioned are applied here whereas the hardware second stage trigger, as simulated above, restricts TDC values to a 350 ns window.

A further "fireball" cut to eliminate electronic noise is applied. The "fireball" cut is necessary because when an excessive amount of charge was input to a single discriminator card of 16 channels, all or most channels on that card would fire. Since all of the discriminator electronics is divided into 16 channels per card we would occasionally have one or two cards, and thus as many as 16 or 32 contiguous cells,

Figure 47. An Example of a Shower Contaminated by a "Fireball" Occurrence in DC2. Radius of "Hit" Proportional to Drift Distance to Sense Wire.

indicating hits. An example of such a fireball event is shown in figure 47 where the fireball occurred in DC2.

To eliminate these "fireball" events, we establish a cut within the analysis on the number of contiguous wires firing in any of the three drift chambers. To determine the best value of this cut, a separate data set of 5,000,000 Monte Carlo IB events above 30 MeV were produced using the same detector geometry used to acquire data, simulating inner bremsstrahlung photons without applying the second stage filter at event generation. These events yielded 40,000 events which passed the simulated first stage trigger. Figure 48 shows the maximum contiguous number of cells firing for inner bremsstrahlung events for both real data and Monte Carlo simulations. The two data sets are given a common normalization. It is clear from comparing the 2 curves that a cut to eliminate contiguous widths of 10 or more is indicated, as the 8% of real events occurring above this cut are primarily due to fireball events as is

Figure 48. Maximum Contiguous Width: Inner Bremsstrahlung Showers

evident in the peak at 16. Figures 49 and 50 show the same type of data for cosmic ray data and pion data, respectively, acquired during the run. Further examination of these figures indicates, as expected, that fireball events are most frequent for pion data. They occur in 15% of events, where the converted pair will be ~ 50 -80 MeV, depending on the kinetic energy of the π^0 when it decayed. The pair will orbit within the drift chambers multiple times producing a great deal of charge within the drift chambers through ionization. The inner bremsstrahlung pairs will be typically 30-50 MeV, producing somewhat less ionization within chambers. Cosmic rays, typically 2 GeV, are too energetic to orbit back into the drift chambers and deposit more energy into the chambers.

Figure 49. Maximum Contiguous Width: Cosmic Ray Events

The particular order of application of the various cuts in the second stage filter is as follows. For a given shower, the aforementioned TDC cuts are applied to eliminate long drift time hits. Drift distances are then calculated based on the drift time to drift distance calibrations already discussed. A few hits are above the 300 channel calibration region but fall below the TDC cut values. These hits are given maximum drift distances corresponding to the furthest extents of the cell in question and are treated in the circle fitting section of the code. The cuts are then applied in the order listed in table 8 with surviving showers then fed to the circle fitting algorithm. If the shower fails one of the final two cuts, or if the fitting algorithm fails to successfully fit the particle orbits, the shower is scanned for a subset that will satisfy the cuts and

Figure 50. Maximum Contiguous Width: Pion Data

fitting algorithms until the particular subset can no longer satisfy minimum shower requirements. The shower scans for subsets by anchoring the low phi end of the shower and incrementing, hit by hit, from the high phi end of the shower inward. This process is then repeated as the anchor is moved toward the high phi end of the shower. The filtering rates for run 1200 are shown in table 8 with the analogous Monte Carlo results included. These rates are for all showers including legitimate pairs, comptons and any other showers. The filtering rates predicted by the Monte Carlo for various relevant shower types are discussed in the next sections. The discrepancies are mostly in the DC2 fail codes (too few DC2 hits or too narrow in DC2). This is due to soft

Table 8. Filtering Rates for the Software Second Stage Trigger: Real versus Monte Carlo

Reason For Failure	Monte Carlo	Run 1200
problem event (array overflow etc.)	0	0
too few dc2 hits	22.3	28.5
too few dc3 hits	4.0	4.9
too narrow in dc2	25.7	29.4
too narrow in dc3	2.9	2.4
fireball in dc1		1.9
fireball in dc2		0.9
fireball in dc3		0.3
DC2 pattern requirements failed	3.2	3.8
too few DC3 hits with DC2 hits nearby	17.2	15.5
passed second stage filter	24.7	12.3

(all numbers in %)

photons generated by Michel positrons incident on the Pb sheets beneath the electron scintillators, as mentioned earlier.

IV.5.3 Pattern Recognition and Circle Fitting

A typical energetic shower is shown in figure 51 with the fitted particle tracks shown passing through the vertex and both edges of the shower. Hit drift cells are indicated as circles with radii indicating drift distance to the sense wire. The vertex of the shower is indicated as located by the code. It is located only to within ± 1 cell by the code. The edges of the shower are also marked. The edges are where a pair member orbits back into the drift chambers and is located by the analysis code as the furthest extents of the shower consistent with pattern requirements required by the code. It should be noted that Figure 51 is an unusually clean shower selected for

Figure 51. A Typical $\mu \rightarrow e\gamma\nu\bar{\nu}$ γ -Shower.

illustration. A more realistic shower may be much noisier and several possible edges or vertices may be located before a successful fit is achieved.

The circle fitting algorithm consists of 3 parts: The event classification section, the vertex location or pattern recognition routines, and the actual fitting section. The shower hits are first grouped into contiguous "clusters" of hits in each DC layer. This makes edge and vertex location easier as well as selection of particular cells to include in the fit.

The showers that pass the second stage trigger are fed to the edge routine for classification as 2-3, 3-2, or 3-3 showers. The classification is done according to how far the shower members penetrate into the drift chambers as they orbit through the drift chambers. We list the positron first so that a 3-2 shower has the positron penetrating as far as DC3 and the electron as far as DC2. Figure 52 shows a typical

Figure 52. 3-2 γ -Shower

asymmetric shower, a 3-2 shower in this case while figure 51 shows a 3-3 shower. Any shower with one of its members penetrating only as far as DC1 will contain too little information to do a successful trajectory reconstruction on that side of the shower and is discarded. If a shower is of type 2-2, it is of low energy and of no interest here. To find the edges and classify the shower, the algorithm scans the shower for edges from the outer extents of the shower inward. The code starts by looking for the low phi end or the positron edge and scans the shower from there inward. When and if an edge is encountered, the algorithm then scans from the high phi end of the shower, looking for the electron edge. When a cluster of hits is encountered, the code scans the cluster to see how far into the DCs the cluster penetrates in a reasonable distance from the outer edge of the particular cluster. Various patterns are tested for to allow for things such as a hole in DC2 on the 2 side of a 2-3 or 3-2 shower where the 2

member diverged sufficiently from the vertex to leave such a hole. Figure 53 shows such a hole above the vertex in DC2. At most two clusters are checked for edges on each side of the shower. This should not result in the loss of any legitimate showers, as a subset of the current shower may be resubmitted to the algorithm if the subset still satisfies minimum shower requirements. The performance of the algorithm in successfully or unsuccessfully fitting a given shower is shown in table 9.

Table 9. Number of Fits Attempted Prior to Acceptance or Rejection of the Shower: Monte Carlo versus Run 1200

TRIES	MONTE CARLO		RUN 1200	
	FIT	NO FIT	FIT	NO FIT
1	.959	.995	.992	.900
2	.041	.005	.008	.094
> 3	<.001	<.001	<.001	.006

For Monte Carlo data the algorithm is efficient in processing showers as >99.9% of successful fits are attained on the first two attempts whereas >99.9% of rejected showers are rejected on the first two attempts. For run 1200 data the showers are noisier due to crosstalk effects and background from the electron scintillator Pb annulus.

Figure 53. 3-2 γ -shower with a Hole above the Vertex.

This results in more showers being rejected as in tables 7 and 8 and more attempts being made to fit these "noisy" showers prior to rejection.

Table 10 shows the efficiency of edge at classifying Monte Carlo shower types accurately. The shower types here are the "true" types as determined from the Monte Carlo history file and the numbers listed are the fraction of showers classified correctly. The "true" shower type is determined in the Monte Carlo code by simply tracking the pair members from the known vertex through the drift chambers. It shows the same for legitimate pairs produced in the Pb converters only. We use these true "pairs" throughout this chapter in evaluating the filtering and fitting code, unless otherwise specified. As we will see in the next section, the showers not falling

into the latter category are primarily either Compton scattered electrons or "deep" showers produced below both Pb converter sheets. For our Monte Carlo data set, 95% of these "deep" showers were either Compton showers or highly asymmetric showers where the low energy particle fails to reach the drift chambers. These are 0-3 or 3-0 showers in reality but are wrongly identified as 3-3 showers by the edge algorithm. Most of these wrongly classified showers are suppressed by the various filtering and fitting stages and will be detailed further in the following section. The edge algorithm clearly does an excellent job of classifying showers.

Table 10. Accuracy of Edge Classification of Monte Carlo Showers. All Showers and Pairs Produced in Pb Converters. Showers Classed by "True" Type (2-3,3-3,3-2).

Shower Type	All	Pairs
all	.918	.948
2-3	.868	.867
3-3	.930	.967
3-2	.882	.891

Table 11 shows the distribution of shower types 2-3, 3-2 or 3-3 for run 1200 and Monte Carlo data. Monte Carlo pairs as well as successfully fitted showers for both data types are shown. The distribution of energy shared between the pair is flat, so our detector geometry and the radial conversion locations determine the shower type distribution. The Monte Carlo results match the run 1200 results very

closely for showers classified by edge prior to any further filtering. The table also shows the distribution for legitimate "pairs" produced only within the Pb converters. As expected, the relative occurrence of 3-3 pairs decreases since Compton showers are primarily classified as 3-3 showers. Table 11 also shows the final shower type distributions for those showers remaining after all filtering and fitting stages. The Monte Carlo and run 1200 distributions are reasonably close.

Table 11. Distribution of Shower Types as Determined by the Edge Algorithm: Run 1200 versus Monte Carlo. Results for All Showers Processed by the Algorithm and Only Those Yielding a Successful Fit are Shown.

Shower Type	Run 1200		Monte Carlo		
	all	fit	all	pairs	fit
2-3	.063	.119	.067	.079	.104
3-3	.867	.769	.863	.839	.788
3-2	.069	.112	.070	.082	.108

Once the showers are classified as 3-2, 2-3 or 3-3, or rejected as the case may be, they are fed to the vertex finding algorithms. For 3-2 and 2-3 showers, the vertex is found by scanning the shower from the 2-edge toward the 3-edge to find where DC3 was penetrated on the far side of the vertex. The vertex is then located by scanning the DC1 cluster below the DC3 penetration. If the pair trajectories are as in figure 52 and do not diverge, the vertex is identified as being just to the 2-side of where the vertex penetrates DC3. If they diverge, as in figure 53, the vertex is located as just to the 2-side of where the vertex penetrates DC2 on the 3-side of the vertex. A

3-3 shower with an inefficiency in DC3, as in figure 54, is mis-identified as this latter type of shower. This shower will be selected as one with a gap in DC2 between the vertex and the 2-side of the shower, as in figure 53. The edge may also be missed or misidentified if a similar inefficiency occurs in DC1 or DC2. To guard against these problem showers, a limit of 5 cells is put on any possible gap in DC1 between the vertex and the 2-edge. For all 2-3 and 3-2 showers, a limit of six cells is put on the width of the 2-side of the shower to guard against excessively noisy showers.

Figure 54. 3-3 Shower Mis-identified as 3-2 Due to DC3 Inefficiency.

For 3-3 showers, the pattern recognition algorithm is designed to utilize the MWPC. As the MWPC was not operational in 1990, vertex location for 3-3 showers was done bypassing the MWPC section of the algorithm, but it is worthy of mention here. The MWPC section of the code scans the drift chambers for candidate vertices,

checking the MWPC below each candidate. For a photon conversion in the outer Pb layer, the MWPC will not register an MWPC hit beneath the vertex. Subsequent traversals of the MWPC by a pair member will register a hit in the MWPC beneath each track. This makes the vertex region easily distinguishable from other tracks for this type of photon conversion. If a pair member orbits back too near the vertex region registering a hit beneath the vertex, the above algorithm will not work. For a photon conversion in the inner Pb converter, scintillators or below, or if the above algorithm does not work for an outer Pb converter shower, an alternate algorithm is used. The alternate algorithm is also used for all 1990 data.

In the alternate algorithm, the DC's are scanned for a pattern that may be a vertex. The middle $\frac{2}{3}$ of the shower is scanned. The algorithm performs a sophisticated search for patterns consistent with a $\gamma \rightarrow e^+e^-$ vertex. The width of the vertex region in DC1 is limited to two cells. This is done to filter out showers that originate deep within the detector, below the Pb converters. These showers will tend to diverge before reaching the DC's and present a wide vertex region in DC1. This width cut also eliminates showers in which an additional cell in the DC1 vertex region fires due to electronic noise or crosstalk from an adjoining cell. Some showers are also lost if a pair member orbits back to within <1 cell of the vertex region, contaminating the region and making it artificially wider. Table 12 shows the efficiencies for the algorithms to find a vertex for both run 1200 and Monte Carlo data without the MWPC used in the 3-3 vertex location algorithm. Monte Carlo results are shown for all showers and for pairs only. Also, to measure the improvement in 3-3 vertex location the MWPC is programmed back into the algorithm. The same data set is reanalyzed and results

shown parenthetically in table 12. An improvement of 6-9% is seen in the algorithm when the MWPC is included in the 3-3 vertex location algorithm. The efficiencies are also shown for a Monte Carlo data set utilizing the scintillator-MWPC trigger and including the MWPC in 3-3 vertex location as above. These results are shown in the final two columns of table 12.

Table 12. Efficiencies for Locating a Vertex for All Showers and Specific Shower Types: Run 1200 versus Monte Carlo Data for All Showers and "Pair" Showers Only. Efficiencies Including MWPC in 3-3 Vertex Routine are Shown Parenthetically. Monte Carlo Data Also Processed Using Scint-MWPC Trigger.

Shower Type	Run 1200	Monte Carlo Data		MWPC-Scint.	
		all	pairs	all	pairs
all	.522	.622(.678)	.816(.890)	.642	.871
2-3	.978	.979	.989	.973	.987
3-3	.461	.566(.625)	.782(.871)	.577	.840
3-2	.890	.984	.994	.973	.980

The error in locating the vertex is shown in figure 55 for successfully fitted pairs. Again, the successfully fitted showers will exclude most of the Compton showers and deep showers. The precision for these fitted showers is ± 1 cell FWHM. An error of ± 1 cell is not significant as the vertex region can be several cells in width. The algorithms used to select drift chamber cells to be included in the circle fit rely much more on the cluster itself than the actual vertex location selected. The precision attained is more

Figure 55. Vertex Location Error for Monte Carlo Data Set.

than adequate as succeeding portions of the code use the vertex location information to complete the final, much more precise fit.

Once the vertex and edges of a given shower are located, the shower is fed to several algorithms to select the particular wires to be fed to the circle fitting algorithm. These algorithms use the edge and vertex information already determined and scan only the clusters signified as containing the edges and vertex. For the 3 edges, the code simply tracks the clusters of DC hit cells from DC1 through DC2 and DC3 toward the vertex region, or straight up for an energetic particle. For 2 edges, the particle is traced from the edge back to the vertex and appropriate cells selected. For the 3 side of a vertex the cells in the track are selected much the same as for a 3 edge,

with allowances made for the presence of a track due to an energetic shower member orbiting back near the vertex. There is little that can be done if the secondary track is directly through the vertex. If however, the secondary track leaves at least one cell between it and the vertex, possible contamination is assumed in DC2 and DC3 and only one cell each for DC2 and DC3 are selected for the circle fit on the contaminated side of the vertex. For the 2 side of the vertex, the vertex cells are selected as part of the 2 edge selection code. Much the same logic is used as was used to locate the edges and vertex with various restrictions to allow for noisy showers or cells within the vertex or edge that failed to fire.

The selected wire center locations are then fed to a least squares fitting program that performs an unweighted circle fit to obtain a "rough" circular fit to the particle trajectory. The circle center coordinates of the resulting fit are used to make drift distance corrections for each hit cell. Corrections are made along the ray connecting the circle center and the particular wire center. A correction radially outward from the wire and away from the circle center defines a left ambiguity, a correction radially inward and toward the circle center defines a right ambiguity. This results in each wire having 2 ambiguities.

Next, uncertainties in the hit positions are assigned to each hit cell for the final weighted circle fit. If the particular cell is unambiguously due to the passage of a single member of the pair a relatively small uncertainty is assigned, calculated as $\sigma = d_{\text{cres}} \cdot v_{\text{drift}}$ where d_{cres} and v_{drift} are typical drift time resolution and drift velocity values for an argon-ethane 57/43 gas mixture. These values are 2.14 ns for

dcres and .005 cm/ns for vdrift, resulting in a sigma of .0107 cm or .025 cm FWHM, consistent with the drift time calibration errors we estimated previously.

If the cell is in the vertex region and has been traversed by both particles, a much larger uncertainty is assigned. Initially a sigma of $\frac{1}{\sqrt{12}}$ of the cell width is assigned. This is the sigma for a square distribution with full width equal to the cell width. A further correction is made to the sigma to allow for non-square cells. For a rectangular cell whose width is twice its height, the uncertainty will be less for a hit cell above the circle center than for a cell to the right or left of the circle center. The uncertainty in the ambiguous cell drift distance is therefore corrected depending on where the cell is located relative to the circle center coordinates obtained in the unweighted fit. For our DCs, the aspect ratio is 4 to 5 for height to width, so the correction is not large. These drift distance uncertainties are typically .25-.30 cm sigma, calculated as above. These values are about 25-30 times those assigned for cells hit by only one particle.

A small fraction of hit cells have drift times greater than $t_0 + 300$ channels used for the drift distance calibration but below the $t_0 + t_{dcut}$ values determined previously to eliminate crosstalk between cells and improve overall efficiency. These cells are assigned an intermediate sigma uncertainty of .10 cm. Initial fits assigning a .0107 cm weight to these wires were improved by weighting these wires at .25-.30 cm and improved somewhat more by adopting the .10 cm weight. The weight was varied in Monte Carlo and the perpendicular momentum error, defined as the difference between the actual and fitted values, was compared. No qualitative improvement was observed so the weight was fixed at .10 cm.

Next, a particular ambiguity is selected for each DC cell, the ambiguity being in whether the particle orbited to the left or right of the sense wire. All possible combinations are fitted. Since each cell has 2 ambiguities associated with it, there are 2^n possible combinations of ambiguities. The unweighted circle fit center coordinates are used to make drift distance corrections. When all drift corrections are made a weighted least squares fit is performed, using the weights as assigned above. As the 2^n fits are performed, the best fit, the fit with the lowest chi-squared value, is kept. Through this "chi-squared minimization" the best possible fit may be found. Additionally, we apply a constraint on the fitted circle center coordinates. Figure 56 is a histogram of the radial positions of fitted circle centers relative to magnet center. Clearly, some of the more extreme values imply pair creations either too far below the detector mass or too far above the outer Pb converter to be reasonable. Figure 56 suggests a cut on the circle center position between 32 and 36cm. These positions effectively limit pair production to a more realistic radial region and eliminate unrealistic fits due to noise, contamination or crosstalk in the DCs. If a fit fails to pass this cut, it is rejected and the chi-squared minimization is continued for the remaining ambiguities. A more detailed analysis, itemizing the entries of figure 56 into 2-3, 3-2 and 3-3 components results in spectra very similar to figure 56 except that the 2-3 and 3-2 components show a distinct drop at the position of the in Pb converter annulus. This is due to the 2-member of the pair having its center very near the Pb converter annulus. The itemization described indicates that a separate circle center radial position cut is not necessary. When all 2^n fits have been performed, we are left

Figure 56. Radial Position of Fitted Circle Center: Pb Converters are Located at 33.64 cm and 34.60 cm. Additional Chamber Mass (Al. and Scintillators) is Located Below 32 cm.

with the lowest chi-squared fit. If none was found below a chi-squared of 10,000 the shower is discarded.

The cumulative effect of the various filtering and fitting stages is shown in table 13. Effects are shown for run 1200 and Monte Carlo showers. The Monte Carlo rates for all showers and "pairs" only are shown for comparison. Shown at each filter stage are the cumulative effect expressed as the number of showers remaining per μ -stop ($\times 10^6$) in the target (column A) and the individual effect at each filtering/fitting stage (column B). The first and second stage trigger rates have been discussed previously.

The other filtering/fitting stages differ between the run 1200 data and the Monte Carlo data for all showers. The differences are primarily due to crosstalk effects in the run 1200 data set. As mentioned previously, the "pairs" exclude Compton scattered electrons and "deep" showers and are typical of the showers remaining after all filtering/fitting stages. The various stages are very efficient for these "pairs" and indicate a high rejection rate for Compton scattered electrons and deep showers. The filtering rates for Comptons and deep showers will be treated in the next section.

Table 13. Filtering and Fitting Efficiencies at Various Stages. "ALL" Monte Carlo Showers, Monte Carlo "PAIRS" and Run 1200 Data are Included for Comparison. Column A: Showers Remaining per μ -stop ($\times 10^6$). Column B: Efficiency (Success) at Each Stage.

	ALL		PAIRS		RUN 1200	
	A	B	A	B	A	B
First Stage	22.5	.047	6.53	.018	23.0	
Second Stage	9.45	.419	5.64	.863	4.84	.211
Edge Finder	9.05	.958	5.52	.979	4.33	.892
Vertex Finder	5.63	.622	4.50	.816	2.27	.522
$\chi^2 < 10000$	5.57	.989	4.48	.995	2.23	.984
$\chi^2 < 150$	4.79	.859	3.98	.889	1.48	.664

A low statistics perpendicular momentum spectrum is shown in figure 57 including both run 1200 and Monte Carlo results. Correspondence of the two curves is reasonable and any differences at this level are purely statistical or due to crosstalk effects. The low energy tails of both spectra match very closely. As already discussed,

Figure 57. Perpendicular Momentum for Run 1200 versus Monte Carlo Data.

the Monte Carlo was smeared twice to achieve the correspondence between Monte Carlo and run 1200 data shown in figure 57. The high energy spectra of the two data sets also correspond closely. The small difference may be due to crosstalk effects, low statistics or the presence of high energy photons due to annihilation in flight of Michel positrons produced within the target. The annihilation in flight question will be discussed in a later chapter. In this later chapter, all available LAMPF 1990 inner Bremsstrahlung data will be included in the perpendicular momentum spectrum along with comparable statistics for Monte Carlo data. Increased statistics will also permit us to make a valid comparison of the two spectra, Monte Carlo versus real data, for energies above 50 MeV.

Figure 58 shows the perpendicular momentum error for all Monte Carlo fits, comparing fitted values to true values of the shower perpendicular momenta, indicating an error of 900 keV FWHM.

Figure 58. Monte Carlo Error on Perpendicular Momentum.

The perpendicular momentum fit chi-squared value for all fits are shown in figure 59. The values histogrammed are total values for both pair members. Run 1200 values and Monte Carlo values are both shown for comparison. Spectra are normalized to a common maximum for illustration. The shoulder in the run 1200 curve is primarily due to crosstalk effects as discussed previously. A chi-squared cut

of 150 is indicated to eliminate bad and probably incorrect or faulty fits. The tail in the run 1200 spectrum at high chi-squared values is more pronounced than the Monte Carlo spectrum. This again is due to the presence of crosstalk in the run 1200 data.

Figure 59. Chi-Squared Values for Successfully Fitted Showers.

Figure 60 shows the spectra of figure 59 for showers below the chi-squared cut of 150. It also shows the chi-squared spectrum for a single smear in the Monte Carlo

Figure 60. Chi-Squared Values for Successfully Fitted Showers with Chi-Squared Values Below 150.

data. The double smear spectrum, as already discussed, reproduces the crosstalk shoulder much more closely than the single smear spectrum.

IV.6 Compton Electrons and Deep Showers

The primary source of difficulties in the various stages of the filtering and fitting codes are Compton scattered electrons and "deep" showers produced below the inner Pb converter layer. These sources of "background" may degrade the performance of our detector and it is therefore important to understand the effectiveness of the various filtering and fitting stages in eliminating these showers. We therefore use our Monte Carlo data sets to evaluate these background showers. The background

rates we observe here for the innermost photon spectrometer layer are higher than for any of the outer layers because of the presence of the positron detector tension shell, located immediately inside of the innermost spectrometer layer.

Table 14. Filtering Rates for Various Shower Origins. Column A : Showers Remaining per μ -stop ($\times 10^6$). Column B : Efficiency (Success) at Each Stage.

	PAIRS		COMPTONS		DEEPS	
	A	B	A	B	A	B
First Stage	6.53	.018	2.26	.019	8.15	.046
Second Stage	5.64	.863	.726	.321	1.29	.158
Edge Finder	5.52	.979	.702	.966	1.25	.965
Vertex Finder	4.50	.816	.099	.141	.273	.219
$\chi^2 < 10000$	4.48	.995	.092	.926	.255	.933
$\chi^2 < 150$	3.98	.889	.057	.620	.187	.734

The Monte Carlo data set used in the previous section was reanalyzed twice; once processing only Compton scattered electrons, including those produced in and below the Pb converters, and once processing only deep showers, including both Compton produced showers and legitimate pairs produced below the Pb converters. The filtering rates for legitimate pair showers, Compton showers and deep showers is shown in table 14. The pairs analyzed here are only those produced in the Pb converters. The first column, column A, for a particular class of particle gives the showers remaining after that stage expressed as per μ -stop ($\times 10^6$). Column B is the efficiency (fraction passing) of each stage.

The Compton electrons, electrons scattered primarily from the scintillator and aluminum mass below the Pb converters by energetic photons, may be mistaken for legitimate showers if they are energetic enough. Table 14 indicates that they are filtered at about the same rate. Those that pass will do so for energetic reasons. The second stage trigger will be a more effective filter against Compton scattered electrons as those that orbit through the chambers only once will produce too few hits in a given DC to pass the filter. The surviving showers are then fed to the edge routine. Since energetic Compton electrons surviving to this point will have fairly distinct edges, the showers are selected as 3-3 showers and passed to the vertex location algorithm. For our Monte Carlo data set 100% of Comptons were selected as 3-3 showers. The vertex finding stage of the fitting code is much more effective in filtering the remaining Compton showers. The code specifically discards any candidate vertices with one hit in each DC as is the case for Compton electrons orbiting within the DCs for a second or third orbit producing a possible vertex. This stage results in 88% suppression of the Compton showers.

The Compton showers fed into the circle fitting algorithm tend to have large chi-squared values as the drift distance profiles in the vertex region are inconsistent with a legitimate vertex. The chi-squared cuts result in $\pm 40\%$ suppression of the surviving Compton showers. For all filtering and fitting stages we see that the Compton showers are suppressed at a rate 25 times that for legitimate pairs.

Deep shower filtering rates are very close to Compton filtering rates because 89% of the Compton showers in our Monte Carlo data are deep showers. If a deep shower is asymmetric the low energy member of the shower will be unable to penetrate into

the DC's and the energetic half of the pair should then be filtered exactly as if it were a Compton electron. A symmetric deep shower will usually not produce a discernable vertex as the pair members will diverge from one another before penetrating the DCs. Only very energetic pairs will reach the DCs before diverging and produce a discernible vertex. These pairs are of interest to us as they may approach 52.8 MeV energy and may constitute candidate $\mu \rightarrow e\gamma$ decay events. The first stage filtering is much more effective than for Compton showers because showers will appear less energetic (narrower) for either the scintillator only or the scintillator-MWPC triggers due to their deeper conversion. The second stage trigger is more effective for the same reason. The vertex finding algorithm, while much more effective at suppressing deep showers than legitimate pairs, is not as effective as for Comptons. This is because 11% of the deep pairs are legitimate e^+e^- pairs produced in the scintillators, and should lead to successful fits if they are energetic enough to pass the first and second stage triggers and symmetric enough to form a discernable vertex in the drift chambers before the pair members diverge.

The $\chi^2 < 150$ cut eliminates 11% of the legitimate pair fits. It is more efficient in eliminating Comptons, eliminating 38%. This is expected as the Compton scattered electrons successfully fit are by definition wrong fits. The deep pairs are rejected at an intermediate rate, 27%, because of the legitimate high energy pairs among the deep pairs.

Table 15 shows the fraction of each shower type both before any filtering and after the final fit and chi-squared cuts. Here, pairs refers to all legitimate pairs, regardless of their classification as 3-2, 3-3 or 2-3 during fitting or their conversion

location. It is clear that the filtering and fitting stages are very effective in eliminating most Compton showers and deep pairs. A more important issue is the suppression of the above background sources for 52.8 MeV photons. This issue will be addressed in the next chapter.

Table 15. Fraction of Shower Types before and after Filtering and Fitting

	PAIRS	COMPTONS	DEEPs
Initial	.753	.247	.436
Final	.989	.012	.029

CHAPTER V

52.8 MEV PHOTONS

In the previous chapter it was shown that, within the limitations of our detector system in 1990, the photon detector and its accompanying analysis software is capable of achieving 0.90 MeV/c FWHM resolution for transverse momentum of the internal Bremsstrahlung spectrum above 30 MeV/c. It was also shown that the filtering and fitting algorithms are rather efficient at eliminating various "undesirable" showers, including Compton scattered electrons and "deep" showers not produced in either Pb converter annulus. The more crucial question, however, is how the detector and analysis algorithms perform for 52.8 MeV photons as MEGA is primarily interested in these photons. As we now have a roughly calibrated Monte Carlo code, to within the limitations of the 1990 LAMPF data set, we are able to evaluate the detector and analysis code for 52.8 MeV photons utilizing this code.

As in the previous chapter, we analyze the Monte Carlo data as several (sub)sets:

1. all showers;
2. only "legitimate" pairs, those e^+e^- pairs produced only in the Pb converters;
3. only Compton scattered electrons; and
4. only "deep" showers, those showers originating below the Pb converters (in scintillator or aluminum).

Type 1 is used to evaluate the overall performance of the filtering and fitting codes for all detector generated showers while the other three types are used to evaluate

performance for "legitimate" pairs (type 2) and various "background" sources (types 3 and 4). As mentioned in the previous chapter, we expect these background rates to be higher than for spectrometer layers two and three due to the presence of the positron detector tension shell immediately inside of the innermost photon spectrometer layer.

V.1 Efficiencies and Performance of the Detector and Software for $\mu \rightarrow e\gamma$ photons

To evaluate the detector and software for the detection and successful fitting of 52.8 MeV photons, we produce two Monte Carlo data sets. Both data sets are generated for 52.8 MeV photons; one applies the scintillator-only first stage trigger while the other applies the scintillator-MWPC trigger. Both data sets are generated for dip angles between 10° and 45° corresponding to the range of the photon detector utilized for the $\mu \rightarrow e\gamma$ measurement. The dip angle is defined as the angle from the median (x-y) plane of the detector, or 90° -(polar angle). The first data set is analysed assuming no MWPC information and the second data set is analysed assuming a fully functional MWPC. Since typical perpendicular momentum values are much larger here we expect higher detector efficiencies so that only 1,000,000 photons are simulated, resulting in $\sim 56,000$ showers passing the first stage trigger in each Monte Carlo data set. The perpendicular momentum spectrum of showers passing the first stage trigger is shown in figure 61 for both data sets. The momentum shown is the momentum of the pair as they enter the drift chambers, after pair production, scattering and $\frac{dE}{dx}$ ionization losses in the chamber mass below the drift chambers. As in the analogous spectrum, figure 46 of the previous chapter, the scint-MWPC first stage trigger makes a fairly distinct momentum cut, in this case at ~ 35 MeV/c

compared to the somewhat rougher cut for the scint-only trigger of $\sim 30\text{-}40$ MeV/c. The spectra here average ~ 45 MeV/c, 5-10 MeV/c higher than the analogous inner Bremsstrahlung spectra of figure 46, as it should be for the more energetic incident photons.

Figure 61. Perpendicular Momentum Spectra for Showers Passing the First Stage Trigger. Both Scint-MWPC and Scint-only First Stage Trigger.

Table 16 shows the efficiencies for the various filtering/fitting stages for both Monte Carlo data sets. Column A shows the number of showers remaining per incident photon ($\times 10^3$) at a particular stage. Column B shows the fraction of showers passing

Table 16. Filtering and Fitting Efficiencies at Various Stages for Both Monte Carlo Data Sets for "ALL" Showers and Legitimate Pairs. Column A : Showers Remaining per Incident Photon ($\times 10^3$). Column B : Efficiency (Success) of Each Stage.

	SCINT-ONLY				SCINT-MWPC			
	ALL		PAIRS		ALL		PAIRS	
	A	B	A	B	A	B	A	B
Interactions	111.	.111	95.8	.096	111.	.111	95.7	.096
First Stage	51.4	.462	27.5	.287	55.6	.500	36.7	.383
Second Stage	35.3	.687	25.0	.909	44.5	.801	33.1	.902
Edge Finder	33.7	.955	23.9	.956	42.4	.953	31.4	.949
Vertex Finder	17.1	.506	15.1	.632	23.9	.563	21.4	.682
$\chi^2 < 10000$	16.8	.983	15.0	.993	23.4	.980	21.1	.986
$\chi^2 < 150$	13.1	.783	11.9	.793	17.6	.753	16.2	.768

that particular stage. The passing rates for the first and second stage triggers should be higher here than in the inner Bremsstrahlung case due to the higher perpendicular momenta of the showers in this case, as discussed above. The filtering rates are generally consistent between the two data sets, scint-only and scint-MWPC. For the first stage trigger and the vertex location code, the rates are consistent with the 6-9% difference we saw in the last chapter for the absence or presence of the MWPC. The second stage filter rates for "ALL" showers differ due to the presence of low transverse momentum tail of figure 61 for showers passing the first stage trigger in the scint-only trigger. This tail is filtered out by the second stage trigger. Figure 62 shows the perpendicular momentum of showers passing the second stage trigger. As expected, since the second stage trigger is MWPC independent, the spectra match closely. Since

the overall yields will differ due to the presence or absence of the MWPC, the two spectra are normalized to a common yield. The rates for legitimate pairs do not differ primarily because "DEEP" pairs are excluded. These deep pairs will appear to have a smaller perpendicular momentum value to the first stage trigger and form much of the scint-only low transverse momentum tail. This tail will therefore be much smaller for legitimate pairs only.

Figure 62. Perpendicular Momentum Spectra for Showers Passing the Second Stage Trigger. Both Scint-MWPC and Scint-only First Stage Trigger. (Normalized to a Common Yield)

Table 17. Filtering Rates for Simulated Hardware Second Stage Trigger for Various Cuts for "ALL" Showers. Both Data Sets are Shown.

Reason For Failure	SCINT-ONLY SCINT-MWPC	
problem event (array overflow etc.)	0	0
too few dc2 hits	36.1	38.0
too few dc3 hits	2.9	2.4
too narrow in dc2	2.1	1.9
too narrow in dc3	11.2	4.9
pattern requirements failed	2.1	0.8
too few DC3 hits with DC2 hits nearby	13.0	9.8
passed second stage filter	32.6	42.1

(all numbers in %)

Table 17 shows the second stage filter rates in more detail. The rates are for "ALL" showers for both data sets. Again, the rates are consistent with the absence or presence of the MWPC in the first stage trigger. The "passed second stage trigger" rates are the fraction of showers passing the second stage trigger and yielding a successful fit. The filtering rates are higher for the DC3 cuts due to the presence of the low transverse momentum tail and deep showers. These deep showers are less likely to penetrate as far as DC3 and appear narrower when they do reach DC3.

Table 18 shows the accuracy of the edge algorithm for classifying showers as 2-3, 3-2, or 3-3 for "ALL" showers and pairs. The pairs here are all legitimate pairs produced in either Pb converter layer. The algorithm is very accurate, particularly for legitimate pairs, and differs from the inner Bremsstrahlung accuracy by 2-3%.

Table 19 shows the shower type distribution. Distributions are included for all showers, "legitimate" pairs and for showers surviving the various filtering and fitting

Table 18. Accuracy of Edge Shower Classification for Both Data Sets. "ALL" Showers and Pairs Produced in Pb Converters Only.

Shower Type	SCINT-MWPC		SCINT-ONLY	
	All	Pairs	All	Pairs
all	.896	.926	.893	.934
2-3	.851	.865	.864	.879
3-3	.906	.942	.898	.947
3-2	.872	.879	.888	.896

Table 19. Distribution of Shower Types as Determined by the Edge Algorithm for Scint-MWPC Data.

Shower Type	Scint-MWPC		
	all	pairs	fit
2-3	.068	.089	.114
3-3	.864	.821	.770
3-2	.069	.090	.116

stages and yielding a successful fit. The distribution is the same as for the inner Bremsstrahlung case of the last chapter. The fraction of 3-3 showers decreases for fitted showers because, as in the inner Bremsstrahlung case, Compton showers, which are always classified as 3-3 showers, are filtered out very effectively. Only the scint-MWPC case is shown here as the portion of both data sets surviving the second stage trigger are identical, as we saw in figure 62.

The vertex location efficiencies for both data sets is shown in table 20. The 3-3 rates are $\sim 2\%$ lower than the inner Bremsstrahlung rate of table 12. This is

Table 20. Efficiencies for Locating a Vertex for "ALL" Showers and Legitimate Pairs for Both Data Sets.

Shower Type	Scint-only		MWPC-Scint.	
	all	pairs	all	pairs
all	.506	.635	.563	.681
2-3	.964	.986	.963	.980
3-3	.441	.576	.501	.627
3-2	.967	.989	.958	.975

due to the more energetic nature of the showers here leading to vertex (and edge) contamination from a pair member orbiting back near the vertex region. For the scint-MWPC legitimate pairs we achieve a high (68.1%) efficiency for locating the vertex. If we include only pairs correctly classified by edge, this efficiency raises to 84.5%.

The vertex location error is shown in figure 63. As in the inner Bremsstrahlung case of figure 55, the code achieves an error, shown in figure 63, of ± 1 cell, more than adequate for the remainder of the fitting algorithm. As stated in the last chapter, as most showers are 3-3's, and are restricted to a vertex no more than two wide, an error of ± 1 cell indicate that the code has located the proper cluster of cells in DC1 containing the vertex. The remainder of the algorithm relies on the proper location of the vertex cluster to select the hit DC cells to include in the circle fits. The circle fitting algorithm should therefore obtain a much more accurate vertex location and, more importantly, an accurate circle fit.

Figure 63. Error in Vertex Location for 52.8 MeV Photons.

Table 21. Number of Fits Attempted Prior to Acceptance or Rejection of a Shower : Both Data Sets.

TRIES	Scint-only		Scint-MWPC	
	FIT	NO FIT	FIT	NO FIT
1	.993	.947	.992	.949
2	.007	.052	.008	.050
> 3	<.001	<.001	<.001	.006

Table 21 shows the number of attempts by the algorithm to fit the showers passed by the second stage trigger. As in the inner bremsstrahlung case, most ($>99\%$) of successful fits are attained on the first attempt while most ($\sim 95\%$) of rejected showers are discarded after one attempt with the remainder being rejected on the second try. This indicates a very efficient shower selection algorithm.

Figure 64. Fitted Transverse (Perpendicular) Momentum Spectra for 52.8 MeV Photon Showers. Scint-Only and Scint-MWPC shown. (Normalized to a Common Yield)

Figure 64 shows the resultant transverse momentum spectra for both data sets after filtering and fitting is completed. As before, the spectra are normalized to

a common yield due to differing filter rates due to the presence or absence of the MWPC. Again, the momentum is the transverse momentum of the pair as they enter the drift chambers. The error, determined by comparison to the true value obtained from the Monte Carlo history file, is shown in figure 65. As in the previous chapter for the inner Bremsstrahlung data, the resolution is ~ 900 keV FWHM.

Figure 65. Transverse Momentum Error for 52.8 MeV Photons Showers.

V.2 Elimination of Compton Scattered Electrons and Deep Pairs

As in the previous chapter, we look at the behavior of the filtering/fitting algorithms in handling various "background" showers. These include both Compton

scattered electron showers and "deep" showers generated below the Pb converter layers. Although there is overlap between the two groups, $\sim 19\%$ of the Compton showers originate in the Pb converters while 78% of deep showers are legitimate pairs. The percentage of legitimate pairs will be somewhat lower for layers two and three in the absence of the positron detector tension shell.

Table 22. Filtering Efficiencies for Various Shower Origins. Column A : Showers Remaining per Incident Photon. Column B : Efficiency (Success) at Each Stage. Scint-only Data Set

	PAIRS		COMPTONS		DEEPS	
	A	B	A	B	A	B
Interactions	95.8	.096	15.3	.015	44.4	.044
First Stage	27.5	.287	4.43	.289	22.7	.513
Second Stage	25.0	.909	2.99	.675	9.23	.405
Edge Finder	23.9	.956	2.90	.972	8.90	.965
Vertex Finder	15.1	.632	0.28	.097	1.81	.203
$\chi^2 < 10000$	15.0	.993	0.26	.940	1.70	.941
$\chi^2 < 150$	11.9	.793	0.14	.511	1.07	.630

Tables 22 and 23 show the filtering efficiencies for Compton electron showers and deep showers for both Monte Carlo data sets. In each table column A shows the number of showers per incident photon ($\times 10^3$) surviving at each stage and column

Table 23. Filtering Efficiencies for Various Shower Origins. Column A : Showers Remaining per Incident Photon. Column B : Efficiency (Success) at Each Stage. Scint-MWPC Data Set

	PAIRS		COMPTONS		DEEPS	
	A	B	A	B	A	B
Interactions	95.7	.096	15.4	.015	44.4	.044
First Stage	24.5	.256	4.63	.301	17.1	.384
Second Stage	24.1	.983	3.60	.777	9.90	.580
Edge Finder	23.5	.975	3.48	.967	9.54	.964
Vertex Finder	19.9	.844	.311	.089	2.19	.229
$\chi^2 < 10000$	19.6	.988	.295	.949	2.08	.948
$\chi^2 < 150$	15.4	.787	.143	.485	1.29	.621

B shows the efficiency of each stage at passing showers. For comparison, each table also includes pairs, those legitimate pairs produced in the Pb converters.

As expected, the filtering is less effective for 52.8 MeV Compton produced showers and deep showers than for the corresponding inner Bremsstrahlung showers shown in table 14. For Compton produced showers, the more energetic nature of these showers will result in more passing at all stages. For deep showers, the more energetic showers will penetrate farther and appear wider in the drift chambers than their inner Bremsstrahlung counterparts. Also the shower at the vertex will penetrate farther into the drift chambers, producing a cleaner and more distinct vertex.

Table 24 shows the overall effect of the filtering for eliminating undesirable showers for both data sets. Although the filtering rates for eliminating these showers are not as high as the rates for inner Bremsstrahlung, see table 15, there are fewer Compton produced showers so that the fraction of Compton produced showers here

Table 24. Fraction of Shower Types before and after Filtering and Fitting.

	PAIRS	COMPTONS	DEEPs
Scint-only			
Initial	.861	.139	.399
Final	.990	.010	.082
Scint-MWPC			
Initial	.860	.140	.399
Final	.992	.008	.073

is reduced to a level about the same as for inner Bremsstrahlung showers. Overall, it appears that background showers are filtered out very effectively.

CHAPTER VI

EXPERIMENTAL RESULTS

VI.1 Muon Inner Bremsstrahlung Data : All Available 1990 Data

In this section we present the results analogous to the previous section but for all inner Bremsstrahlung data accumulated during the LAMPF running period in late 1990. A statistically comparable amount of Monte Carlo results is presented for comparison.

Table 25. 1990 Inner Bremsstrahlung Run Scalars : All Data

Scalar#	Routing Box Signal	Occurrences
1	High E Gamma (1st Stage Trigger)	3251262
10	High E Gamma Triggers (Less Busies)	1867569
66	Beam Gates	5694477
67	100 kHz Pulses	2920177968
68	100 kHz Pulses•Beam Gates	209448868

The run scalars, analogous to table 6, for all available 1990 data are given in table 25. A total of 13 runs similar to run 1200 were taken in sequence. Scalar #67 indicates an integrated data collection time of 486.7 minutes. Scalar #68 indicates an integrated time for beam on target of 34.9 minutes, indicating a 7.2% duty factor. This is consistent with all log entries over the data collection period which list duty factors of 7.1-7.3%. Comparing scalars #1 and #10 gives a 42% deadtime, consistent

Figure 66. Perpendicular Momentum Spectra for All Available 1990 LAMPF Inner Bremsstrahlung Data and a Statistically Comparable Monte Carlo Data Set.

with that for run 1200 in the previous section. The beam slits were set to 8.7, or a muon stopping rate of 4×10^6 μ -stops in the target per second (time-averaged) or 5.6×10^7 μ -stops in the target per second (instantaneous rate). This gives a total of 1.2×10^{11} μ -stops over the entire data collection period. Correcting for deadtime, a (1-.426) factor, we see that a total of 6.9×10^{10} useful μ -stops are available for analysis here. Including a factor of 3.2 to account for the filtering between real data and Monte Carlo data as indicated in table 13 of the previous section, and a .453 factor to account for the loss of data by the inclusion of only the "clean" half of our

Figure 67. Perpendicular Momentum Tail Spectra for All Available 1990 LAMPF Inner Bremsstrahlung Data and a Statistically Comparable Monte Carlo Data Set : $E > 45$ MeV.

detector, we see that we need 1.7×10^{10} Monte Carlo μ -stops to achieve comparable statistics for comparison to the 1990 inner Bremsstrahlung data. Since our final spectra include only showers with perpendicular momentum above 30 MeV, we will generate Monte Carlo photons from muon decay with energies only above 29 MeV. The Monte Carlo calculated branching ratio over this energy range is 2.19×10^{-3} . For a Monte Carlo data set of 5,000,000 such photons, the corresponding number of μ -stops is therefore 2.3×10^9 , indicating that seven such Monte Carlo data sets, which correspond to 1.6×10^{10} μ -stops, would allow for comparable statistical comparison.

Figure 68. Perpendicular Momentum Tail Spectra for All Available 1990 LAMPF Inner Bremsstrahlung Data and a Statistically Comparable Monte Carlo Data Set : $E > 50$ MeV.

The cumulative perpendicular momentum spectra for all available 1990 inner Bremsstrahlung data and the corresponding Monte Carlo data mentioned above are shown in figure 66. The error bars included in the 1990 data in the figure are $\sqrt{N}$ statistical errors. The agreement is very good except for the ~ 40 -50 MeV/c range where the Monte Carlo yield is slightly lower. This can be seen in more detail in figure 67, which displays the spectra over the range in question. This will be further addressed in another section in the context of positron annihilation in flight in the target. Figure 67 indicates good agreement above 50-51 MeV/c. Looking above

50 MeV/c in figure 68 shows excellent agreement with minor discrepancies at 50-51 MeV/c. Again, we will address this later in the context of positron annihilation in flight in the target. Above 52.8 MeV/c in figure 68 we still see excellent agreement between 1990 LAMPF data and Monte Carlo data for the extreme tail region above 52 MeV/c, where both spectra effectively vanish.

VI.2 Positron Annihilation in the Target

Another potentially significant source of background is annihilation in flight of Michel positrons orbiting within the target. We study this source of background photons with a simple Monte Carlo program that generates Michel positrons within our 20 mil thick mylar target. As each positron is generated, it is propagated through the target. Positrons may annihilate in flight with bound atomic electrons, generating a photon background. This background is especially important at energies above 50 MeV where it may contaminate any possible $\mu \rightarrow e\gamma$ signal and contribute to the background signal. The Michel positron spectrum is peaked at high energies so we consider only relativistic positrons here. For these positrons, we may safely ignore magnetic field effects on the positron trajectory within the target since the positrons should exit the target before undergoing any significant magnetic deflection.

Each Michel positron generated is propagated through the target to see if it annihilates in flight, consistent with the well known cross section [42] for this process. If a photon is generated, it is written to a data file readable by our EGS4 Monte Carlo code. These photons are then read into the full Monte Carlo program and propagated through the full detector geometry so they may be realistically studied.

For this purpose, we utilize the full 1990 data set along with the seven Monte Carlo data sets generated for use in the previous section. These Monte Carlo data sets represented 1.6×10^{10} μ -stops. An equal number of μ -stops are generated for the annihilation in flight data set. The resultant annihilation spectrum, processed by our detector Monte Carlo code and filtered and fitted as is the Inner Bremsstrahlung data, is shown in figure 69.

Figure 69. Inner Bremsstrahlung Spectrum with Target Annihilation in Flight Contribution Shown: $>30 \text{ MeV}$, Monte Carlo Shown with Annihilation in Flight Contribution Added in.

Figure 70. Inner Bremsstrahlung Spectrum with Target Annihilation in Flight Contribution Shown: >45 MeV, Monte Carlo Shown with Annihilation in Flight Contribution Added in.

The Monte Carlo spectrum shown has the annihilation in flight contribution added in. The discrepancy we saw in the previous section between 40 and 50 MeV/c has disappeared and the agreement is excellent. We see this in more detail in figures 70 and 71 which clearly show excellent agreement at high momentum. The only region of concern can be seen in figure 69 in the central portion of the perpendicular momentum spectrum between 32 and 37 MeV/c where the Monte Carlo yield is $\sim 10\%$ higher. A possible explanation for this discrepancy is twofold. First, the stopping rate for 1990 was known only to within $\sim 10\%$ so that the relative normalization of the 1990

Figure 71. Inner Bremsstrahlung Spectrum with Target Annihilation in Flight Contribution Shown: >50 MeV, Monte Carlo Shown with Annihilation in Flight Contribution Added in.

data and the Monte Carlo data may be off by up to 10%. Secondly, the resolution of the detector may be worse than estimated earlier in the analysis chapter. A "rough" smearing was done that reproduced Monte Carlo data adequately. These two effects together, lowering the Monte Carlo normalization and broadening the Monte Carlo peak width may eliminate the discrepancy while preserving the excellent agreement of both the low and high momentum tails. Renormalizing the Monte Carlo spectrum of figure 69 by 10% in an attempt to bring the 30-40 MeV/c range of the spectrum in agreement with the LAMPF data, we obtain the spectra of figure 72. The low

momentum tail still agrees very well with the LAMPF data. The high momentum agreement is still very good except for the 44-48 MeV, where the difference is still small as seen in figure 73. The spectra differ to a much lesser extent for the 50-52 MeV/c as seen in figure 74 but the difference is roughly the same as that before rescaling.

Figure 72. Inner Bremsstrahlung Spectrum with Target Annihilation in Flight Contribution Shown: >30 MeV, Monte Carlo Shown with Annihilation in Flight Contribution Added in and Renormalized by a 0.9 factor.

A notable characteristic of figure 69 is the periodic substructure of the spectrum. Closer examination indicates that this substructure, manifested by local peaks

Figure 73. Inner Bremsstrahlung Spectrum with Target Annihilation in Flight Contribution Shown: >45 MeV, Monte Carlo Shown with Annihilation in Flight Contribution Added in and Renormalized by a 0.9 Factor.

occurring approximately 2-2.5 MeV/c apart, occur approximately at the locations of drift cells in DC1. The causes of this structure may be two-fold. Firstly, a secondary hit caused by a pair member re-entering the same drift cell on a subsequent orbit may traverse the cell closer to the sense wire. Since the orbital period of the pair members is well below the drift times involved, the secondary hit will stop the TDC, resulting in an artificially low drift time. This effect will tend to produce more hits closer to the sense wire and lead to the substructure seen. The second possible explanation of the substructure seen is in the fitting algorithm. Specifically, Monte Carlo studies

have demonstrated that when the vertex cell hit in DC1 is traversed by both pair members, and is assigned a larger uncertainty in circle fitting, the algorithm has a weak tendency to fit a circle with the wrong ambiguity at the outer edge due to lack of constraints at the vertex region. This may result in the clumping as seen. This effect may be eliminated by constraining the track to traverse the DC1 vertex cell outside of the drift circle. Studies of this constraint will be performed on the improved data from the just completed 1992 LAMPF run.

Figure 74. Inner Bremsstrahlung Spectrum with Target Annihilation in Flight Contribution Shown: >50 MeV, Monte Carlo Shown with Annihilation in Flight Contribution Added in and Renormalized by a 0.9 Factor.

CHAPTER VII

DISCUSSION AND CONCLUSIONS

The four years of in-beam development and testing of the MEGA experimental apparatus prior to and including the acquisition of data for this document have seen numerous innovations in the evolution of the final detector system. Principal among these has been the Pb-converter support cylinders, the Z-coordinate readout and drift chamber design for the photon spectrometer system and MWPC placement and design for the positron detector system. In fact, the original design as proposed in 1985 bears little resemblance in many respects to the "final" design in place in 1992. Other innovations took place in other aspects of the experiment such as the trigger system and the data acquisition system.

The remainder of this section will discuss the evolution of the detector system with the primary focus being on the photon detector system and its state in the 1990 in-beam tests at LAMPF. Innovations in the positron detector system, the focus of another student's dissertation, will also be briefly discussed, as well as innovations in some peripheral systems.

VII.1 Photon Spectrometer

Support Cylinders

The original photon detector design for the MWPC and three stacked Drift Chambers as implemented in the first cylindrical prototype in-beam tests at LAMPF in 1988 differed markedly from the 1990 design as shown in figure 11. In the original

design, each Drift Chamber consisted of a sense wire plane with alternating field and sense wires and inner and outer cathode foils, each mounted on a Rohacell cylinder, each cylinder supporting the outer foil of a given DC and the inner foil of the next outer DC. For the MWPC, each cylinder also had to support a Pb converter annulus. This design required these five Rohacell cylinders to support the tension of over 2000 wires or over 200 kG of total wire tension. In-beam tests in 1988 as well as post-mortem examination of the wire chambers led to several conclusions. First, the Rohacell cylinders had not attained the required radial precision and uniformity to provide stable performance in either the MWPC or the Drift Chambers. The chambers were very unstable and discharges between cathode foils and adjacent sense wires in areas of reduced half-gap led to numerous discharges causing broken sense wires in both the MWPC and Drift Chambers. Secondly, post-mortem examination of the chambers indicated that the cylinders were significantly deformed axially due to both the large amount of wire tension on the Rohacell cylinders and from transporting the completed chamber the ~1000 miles from the University of Houston to LAMPF in a vertical position. The primary changes made as a result of these problems were several. Firstly, the cathode foil planes were replaced by the cathode wire planes in the current design. This led to a more stable design and required three fewer Rohacell cylinders. This also nearly doubled the number of wires, and thus wire tension, in the final design. To relieve the Rohacell cylinders of the wire tension deformation of the now more than 4000 wires, each photon detector later was physically connected to the Aluminum scintillator support cylinder for the layer immediately outside of it, so

that the wire tension was supported by this cylinder. Also, the Pb converter material was replaced by a Pb-Sn alloy that was more rigid and less subject to gravitational deformations when placed horizontally within the magnet for extended periods. With these modifications implemented, the photon detector was rebuilt for 1989.

The performance of the photon detector in 1989 showed marked improvement over the 1988 tests. Performance of the MWPC, though improved was not adequate due to radial nonuniformities of the two remaining Rohacell cylinders, each supporting a Pb converter annulus and an MWPC cathode foil. Electronics design problems also degraded performance of both the MWPC and the Drift Chambers and, along with cylinder non-uniformity problems, led to the demise of the MWPC early in the 1989 test period. The performance of the drift chambers was adequate for further evaluation and testing in 1989. As a result of these 1989 test runs at LAMPF, and because of construction difficulties in producing Rohacell cylinders to the precision required for adequate MWPC performance, a carbon fibre composite cylinder design was adopted to replace the much weaker Rohacell cylinder material. Development and construction timetables made it impossible to have the new carbon fiber cylinders ready for the 1990 test run at LAMPF which is the subject of this document. It was thus decided that, with electronic design improvements and minimal repairs, the 1989 chamber could be utilized again for 1990 tests.

The performance of the Drift Chambers in 1990 was much improved over previous years, with the principal problems being cross-talk caused partly by electronics problems and "fireball" events as discussed earlier. Both of these problems were handled satisfactorily in off-line analysis and the only observable effects were in the

reduced filtering and fitting efficiency caused by the contamination of events through crosstalk. The MWPC, however, performed poorly even with improved electronics. The Rohacell non-uniformities induced a number of discharges between the cathode foils and adjacent sense wires and resulted in numerous broken wires. This was not in itself fatal to the MWPC. Discharges to the outer MWPC cathode foil, which was mounted on the same Rohacell cylinder as the inner foil of the Drift Chambers tended to induce destructive discharges between the Drift Chamber cathode foil and the inner Drift Chamber sense wires. Rather than risk the ultimate early demise of both the MWPC and Drift Chambers if the discharges continued, it was decided that the MWPC be turned off during the 1990 LAMPF runs to insure the survival of the Drift Chambers. The principal effects of this were felt in both the on-line first stage trigger and eventually in the vertex location algorithm in the off-line analysis.

The recently completed test runs in late 1992 at LAMPF with the carbon fibre cylinders included have performed well. Electronics modifications have eliminated much of the cross talk and fireball events from the Drift Chambers, and the MWPC has performed very well with extremely few discharges experienced.

Z-Coordinate Readout

The initial Z-coordinate readout scheme, which never made it past the feasibility study stage, utilized stereo cathode strips etched into the inner and outer cathode foils of the first and second Drift Chambers. The cathode strips were angled as in the positron chambers, with the outer cathode strips angled in the opposite sense as the inner cathode strips. Unfortunately, because the two pair members orbited in opposite directions, the vertex was often contaminated by the edge hits of one of the

pair members, leading to "ghost" hits which proved difficult to resolve from real hits. This, and ultimately the chamber redesign that eliminated Drift Chamber cathode foils in favor of cathode wire planes, led to the abandonment of this scheme.

The next scheme adopted utilized resistive "stableohm" wires for the inner two drift chamber layers. This design, present in the chamber prototypes through 1990, was eventually abandoned because of both the brittle nature of the stableohm material and the poor resolution seen in initial in-beam tests. Although this scheme was available in 1990, the lack of ADC electronics made useful Z-coordinate readout, even at poor resolutions, impossible. Another scheme, using "chevron" cathodes beneath resistive DC1 sense wires was investigated in bench tests. This scheme relied on resistive wire readout to attain a rough Z-coordinate measurement and the chevron pattern to obtain a more precise z-coordinate measurement locally. This scheme was abandoned due to the degradation in resolution at the interface between connecting chevrons. Another scheme, the scheme eventually adopted in the final design, was tested in-beam at LAMPF in 1990 with a small planar prototype chamber with good results and incorporated into the chamber design for operation at LAMPF in 1992. This scheme uses delay lines beneath each sense wire in DC1. Initial analysis of this data indicates that the design resolution of 5mm FWHM will not be achieved in 1992 due to electronics problems. These problems are being resolved and the design resolution of 5mm FWHM will hopefully be achieved in the 1993 data run at LAMPF.

The principal drawbacks of lacking a Z-coordinate readout in 1990 were twofold. First, only the perpendicular, or transverse, component of the photon momentum was obtainable for further analysis. Secondly, the lack of Z-coordinate information,

along with the lack of vertex location information provided by the MWPC, made it impossible to extract any useful information from any of the π^0 data acquired. A typical energetic π^0 photon would produce an energetic pair that would make numerous orbits through the Drift Chambers presenting numerous candidate vertices. The lack of MWPC and Z-coordinate information made identification of the actual vertex among the many candidates virtually impossible.

Scintillators

Apart from various relatively straightforward electronic refinements, the photon scintillators performed almost to design goals, yielding a timing resolution of ~ 800 ps FWHM compared to the design goal of ~ 750 ps.

Second Stage Trigger

Because of problems encountered with MWPC performance, some of the triggering function of the MWPC was replaced by an alternate trigger. A second stage hardware trigger was installed to be positioned logically immediately after the first stage trigger. Various patterns involving the Drift Chambers are scanned for. This scheme was successfully tested in 1990 at LAMPF but due to electronics problems, it was not fully utilized that year. It will be used in all future runs.

Multiplexing

Various noise studies performed utilizing both the 1989 and 1990 LAMPF data at full beam intensities have led to the conclusion that the multiplexing scheme as adopted up until then results in the folding of background events from another quadrant onto a legitimate shower, contaminating the shower. This passive scheme was replaced by an active multiplexing scheme which utilizes the first stage trigger to

activate readout of the shower area only, turning off the readout from the remainder of the detector, and thus eliminating this background contamination. Monte Carlo studies of this scheme, along with its eventual implementation in the 1992 LAMPF run, have indicated success.

High Voltage Polarity

The various iterations of the wire chambers up until and including the 1990 design have all contained negatively charged cathode planes with grounded sense wires for the MWPC and negatively charged cathode wire planes and field wires with grounded sense wires for the Drift Chambers. In an attempt to insure better MWPC stability, an alternate scheme was suggested where all sense wires were charged to a positive high voltage with cathode foils and field wires grounded or set to a low negative voltage, depending on their location relative to a sense wire. This configuration was tested on the 1990 prototype chamber after the completion of the 1990 LAMPF run. The MWPC was found to be much more stable and the Drift Chambers saw no degradation in performance. This scheme was built into the 1992 design and was successful in all wire chambers.

Layer Three Additional Drift Chamber

Feasibility studies performed partly by this student after the 1990 LAMPF run resulted in a slightly modified design for the third (outermost) photon pair spectrometer. To improve reconstruction capability and efficiency in π^0 shower reconstruction, a fourth Drift Chamber, 2 cm outside of DC3, was added to the design. This outermost spectrometer layer will be installed, along with the remainder of the photon detector system, for $\mu \rightarrow e\gamma$ data acquisition in late 1993.

VII.2 Positron Spectrometer

MWPC's

The positron spectrometer design has undergone as marked an evolution as the photon spectrometer design. The original proposed design consisted of three concentric cylindrical MWPC's. This design was abandoned because the innermost of the three MWPC's was shown to have the majority of cells populated during a given decay event. The design eventually adopted, and tested in various stages in the LAMPF beam in 1988, 1989 and 1990 contained eight MWPC's. The three concentric MWPC's were replaced by a single one positioned as the middle of the original three, with seven identical MWPC's, each the same diameter as the innermost one in the original design, located as discussed previously. Also, the pitch of the MWPC's originally was 1 mm. In 1989 and 1990 this design proved to be somewhat unstable so a wider pitch of 1.3 mm was adopted, with improved performance the result during 1992 in-beam test. Overall, this design has proved promising during in-beam testing at LAMPF and as of the 1992 LAMPF test, the only remaining problem was with electronic design. Recent effort in that direction appears promising.

Scintillators

Apart from initial refinements the electron scintillators have performed about as expected in tests to date.

VII.3 The Future of MEGA

1990 also saw the first instance of the integration of most of the various sub-systems of MEGA into a single, coordinated unit. Some data was acquired by this

integrated system and led to a $\mu \rightarrow e\gamma$ branching ratio of $\sim 10^{-7}$. Although this figure is about equal to the published value from about 1974, the exercise demonstrated that all of the various subsystems that had been developed pretty much independently of one another could function well in coordination.

The primary focus of the 1992 run at LAMPF was two-fold. Firstly, to acquire $\mu \rightarrow e\gamma$ data at least to the level of the currently published branching ratio and secondly, to complete an initial measurement of the ρ -parameter by the positron detector system. Preliminary analysis is promising on both counts. The only real problems encountered during the 1992 run were the positron MWPC electronics, the throughput limitations of the acquisition system leading to frequent deadtime and the electronic limits on photon pair spectrometer delay line resolution. Indications are that, for the 1993 LAMPF data run, the remaining problems should be resolved and the design goal for the $\mu \rightarrow e\gamma$ branching ratio should be attained, as well as a further improvement on the ρ -parameter over the 1992 value.

REFERENCES

- 1 C. D. Anderson and S. J. Nedermeyer, *Phys. Rev.* **50**, 263 (1936).
- 2 C. S. Wu, *Rev. Mod. Phys.* **36**, 618 (1964).
- 3 R. L. Garwin, L. M. Lederman and W. Weinrich, *Phys. Rev.*, **103** 1415 (1957).
- 4 G. Danby, J-M. Gaillard, K. Goulianos, L. M. Lederman, N. Mistry *et al.*, *Phys. Rev. Lett.* **9**, 36 (1962).
- 5 S. Lokanthan and J. Steinberger, *Phys. Rev.* **98**, 240 (1957).
- 6 S. Weinberg, *Phys. Rev. Lett.* **19**, 1264 (1967).
- 7 A. Salam, *A Nobel Symposium*, No. 8, 367 (1968).
- 8 S. L. Glashow, J. Iliopoulos and L. Maiani, *Phys. Rev.* **D2**, 1285 (1970).
- 9 R. D. Bolton, J. D. Bowman, R. Carlini, M. D. Cooper, M. Duong-van *et al.*, *Phys. Rev. Lett.* **53**, 1415 (1984).
- 10 R. D. Bolton, M. D. Cooper, J. S. Frank, A. L. Hallin, P. A. Heusi *et al.*, *Phys. Rev.* **D38**, 2077 (1988).
- 11 R. N. Mohaptra and G. Senjanovic, *Phys. Rev.* **D23**, 165 (1981).
- 12 Y. Tomozawa, *Phys. Rev.* **D25**, 1448 (1982).
- 13 R. P. Feynmann *Quantum Electrodynamics* (Benjamin/Cummings, Reading, Mass., 1961)
- 14 C. N. Yang and R. Mills, *Phys. Rev.* **96**, 191 (1954).
- 15 G. 't Hooft, *Nucl. Phys.* **B33**, 173,(1971); **B35** 167 (1971).
- 16 N. Cabibbo, *Phys. Rev. Lett.*, **10**, 531 (1963).
- 17 M. Kobayashi and T. Maskawa, *Prog. Theor. Phys.* **49**, 652 (1973)
- 18 E. J. Konopinski and H. M. Mahmoud, *Phys. Rev.* **92**, 1045 (1953).
- 19 J. Schwinger, *Ann. Phys.* **2**, 407 (1957).

- 20 T. P. Cheng and L. F. Li, *Phys. Rev. Lett.* **45**, 1908 (1980).
- 21 R. G. H. Robertson, T. J. Bowles, G. J. Stephenson, Jr, D. L. Wark, J. F. Wilkerson *et al.*, *Phys. Rev. Lett.* **67**, 957 (1992).
- 22 K. Hikasa, K. Hagiwara, S. Kawabata, R. M. Barnett, D. E. Groom *et al.*, *Phys. Rev. D***45**, VI.7 (1992).
- 23 K. Hikasa, K. Hagiwara, S. Kawabata, R. M. Barnett, D. E. Groom *et al.*, *Phys. Rev. D***45**, VI.9 (1992).
- 24 A. Cnops , *Phys. Rev. Lett.* **40**, 144 (1978).
- 25 K. Hikasa, K. Hagiwara, S. Kawabata, R. M. Barnett, D. E. Groom *et al.*, *Phys. Rev. D***45**, II.1 (1992).
- 26 L. Kane and R. Thun, *Phys. Lett.* **B94**, 513 (1980).
- 27 S. Dimopoulos and L. Susskind, *Nucl. Phys.* **B155**, 237 (1979).
- 28 P. Fayet and S. Ferrara, *Phys. Rep.* **32**, 249 (1977).
- 29 D. V. Nanopoulos, *Phys. Rep.* **105**, 71 (1984)
- 30 R. Arnowitt and P. Nath, *Phys. Rev. Lett.* **66**, 2708 (1992)
- 31 A. Bean, J. Gronberg, R. Kutschke, S. Menary, R. J. Morrison *et al.*, *Phys. Rev. Lett.* **70**, 138 (1993).
- 32 H. Georgi and S. Glashow, *Phys. Rev. Lett.* **33**, 478 (1974)
- 33 W. Marciano, in *Proceedings of the 8th Workshop on Grand Unification*, Syracuse, NY , edited by K. Wali (Syracuse University Press, Syracuse, NY, 1988)
- 34 K. Hikasa, K. Hagiwara, S. Kawabata, R. M. Barnett, D. E. Groom *et al.*, *Phys. Rev. D***45**, II.25 (1992)
- 35 W. R. Nelson, H. Hirayama, D. Rogers, (1985) *The EGS4 Coding System*, SLAC-Report-265.
- 36 E. Storm, and H. I. Israel, *Atomic Data and Nucl. Data Tables* **7**, 565 (1970)
- 37 Bicron Corporation, Newbury, OH 44065
- 38 Digital Equipment Corporation, Maynard, MA 01754

- 39 CERN, Applications Software Group, Computing and Networks Division,
Geneva 23, Switzerland
- 40 Group MP-1, MP Division, Clinton P. Anderson Meson Physics Facility, Los
Alamos, NM 87545
- 41 Template Graphics Software, Inc., San Diego, CA 92121
- 42 W. Heitler *The Quantum Theory of Radiation* (Dover, New York, 1984)

Supplementary Sources Consulted

- 1 W. J. Marciano and A. I. Sanda, *Phys. Rev. Lett.* **38**, (1977).
- 2 H. Harari, *Phys. Lett.* **B86**, 83 (1979).
- 3 M. A. Shupe, *Phys. Lett.* **B86**, 87 (1979).
- 4 H. Terazawa, *Phys. Rev.* **D22**, 184 (1980).
- 5 H. Fritzsch and G. Mandelbaum, *Phys. Lett.* **102**, 319 (1981).
- 6 Y. Tomazawa, *Phys. Rev.* **D25**, 1448 (1982).
- 7 R. N. Cahn and H. Harari, *Nucl. Phys.* **B176**, 135 (1980).
- 8 LAMPF Research Proposal 969, M. D. Cooper, Spokesperson, Los Alamos Na-
tional Laboratory, Los Alamos, NM. 1985 (unpublished).

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