SEARCH FOR POSITIVELY CHARGED STRANGE QUARK MATTER

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ABSTRACT

SEARCH FOR POSITIVELY CHARGED STRANGE QUARK MATTER

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In this thesis I present the first results of the search for positively charged strangelets in experiment E864 at the Brookhaven Alternating Gradient Synchrotron. E864 is a high sensitivity large acceptance open geometry spectrometer, which is designed to measure rare composite objects and search for strangelets or other novel forms of matter produced in high energy heavy ion collisions. The search was performed for particles with $Z/M < 0.3(GeV/c^2)^{-1}$ produced within $\pm 0.5$ units of the center-of-mass rapidity. This first search enabled us to search probe strangelets with a wide range of masses, including high mass strangelets for the first time at the AGS. A high mass strangelet would be particularly interesting because in addition to the discovery of the strangelet itself, it may signify that a QGP was formed. The analysis uses over 26.5 million “central” events recorded for the “positive strangelet” search from the first (Fall 1994) run of the experiment. The full apparatus was not installed for this run, but the tracking portion of the apparatus which was present for the 1994 run performed to the expectations of our proposal. Thus, we expect that the full apparatus can meet the design goal sensitivity level of $3 \times 10^{-10}/Au+Pb$ central interaction. The number and character of observed high mass candidates are consistent with that expected from Monte Carlo programs, and thus limits are placed on strange quark matter production.
for my parents, Barry and Samoan Barish
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Chapter 1

Introduction

Ordinary nuclear matter is comprised primarily of \( u \) and \( d \) quarks which are confined within nucleons. For example, a carbon nucleus contains 6 protons and 6 neutrons. Each proton consists of two \( u \) quarks and one \( d \) quark, while each neutron contains one \( u \) quark and two \( d \) quarks. Fig 1.1 shows a pictorial representation of a carbon nucleus. The charge \( Z \) in a carbon nucleus is simply the number of protons, while the baryon number \( A \) is the total number of nucleons (neutrons plus protons). One can also imagine a scenario, which is referred to as "quark matter," where the quarks are not confined to nucleons. Quark matter is thus a single color-singlet baryon with baryon number \( A \), which contains a system of \( 3A \) quarks. Quark matter can be subdivided into "nonstrange quark matter" and "strange quark matter" (SQM). Nonstrange quark matter consists only of \( u \) and \( d \) quarks, while SQM consists of roughly equal numbers of \( u, d, \) and \( s \) quarks. "Strangelets" are SQM with baryon number \( A \leq 10^7 \). SQM is defined to be in the "bulk" limit, where \( A \gtrsim 10^7 \), when surface effects can be ignored. Fig 1.1 shows a strangelet which consists of a total of 36 quarks (\( A=12 \)): 13 \( u \) quarks, 13 \( d \) quarks, and 10 \( s \) quarks (\( N_s \)). \( f_s \equiv \frac{N_s}{A} \) is the number of strange quarks per baryon. Quark matter is allowed in the standard model but has been observed. Nonstrange quark matter (\( A > 1, S = 0 \)) is known to be unstable because ordinary nuclear matter does not decay into hadrons with \( A > 1 \). However, the addition of strange quarks opens up the possibility of systems with \( A > 1 \) and \( S \neq 0 \) at least in part due to the Pauli exclusion principle.
Nuclear Matter (Carbon)  
Z=6, A=12 (36 quarks)  
Z/A=1/2

Strange Matter (Strangelet)  
Z=1, A=12 (36 quarks)  
Z/A= 0.083  
N_s=10, f_s=N_s/A=0.83

Figure 1.1: Schematic illustration of the difference between a strangelet and normal nuclear matter.

Quarks are spin $\frac{1}{2}$ fermions, with a spin degeneracy of 2 and a color degeneracy of 3, and thus only 6 quarks of the same flavor may populate a given energy level. This means that the Fermi energy grows rapidly as the number of quarks in the system increases. Therefore, it may be advantageous to add an additional quark flavor, the strange quark, despite the penalty due to the strange quark’s mass. A schematic diagram of the savings in Fermi energy due to the addition of the strange quark is shown in Fig 1.2. As a motivation, a very simple estimate of the total energy of a Fermi gas where the volume is taken as a constant, the quarks are assumed to be massless quarks, and there are an equal number of quarks with each flavor, is given by [1]:

$$E = 4 \left( \frac{k}{3} \right)^{\frac{2}{3}} B^{\frac{1}{2}} \frac{N_{tot}^{\frac{2}{3}}}{N_f^{\frac{1}{2}}} \propto \frac{1}{N_f^{1/4}} \quad (1.1)$$

where $k = \frac{3}{4}(6\pi^2/g)^{\frac{1}{3}}$, $g$ is the degeneracy of the fermion, $B$ is the Bag model constant, $N_{tot}$ is the total number of quarks, and $N_f$ is the number of quark flavors. Therefore, increasing the number of flavors from two to three gives a fractional energy savings of $1 - \left( \frac{2}{3} \right)^{1/4} \approx 10\%$ or about 100 MeV/baryon.
Figure 1.2: Schematic illustration of the energy levels of a system of normal nuclear matter compared to that with the addition of the strange quark.

With the use of quantum chromodynamics (QCD) and the phenomenological bag model more realistic studies of the possible stability of strangelets have been performed. It has been found that there are regions of bag parameter space which allow for the existence of metastable and even stable SQM. See Sec. 1.1.

The existence of strangelets would be interesting for many reasons:

- **Ground state** The existence of SQM could be of fundamental importance because it might be lowest energy state which is stable against strong decay. If this were the case, it would be the true ground state of QGP. Further, SQM were completely stable (more tightly bound than $^{56}$Fe), it would be the true ground state of nuclear matter.

- **Quark Gluon Plasma** If one finds strangelets in heavy ion collisions, the mass and the rate of production of the strangelet would be an indication of how it was produced. A light mass strangelet could be produced by the process of coalescence, while a high mass strangelet is most likely to have come from a quark gluon plasma (QGP). [At a high enough temperature and baryon density, normal nuclear matter is expected to undergo a phase transition to a QGP [2].]
The search for the QGP is a major goal of the heavy ion physics program. This search has proved elusive. While there are many possible signatures of the phase transition to a QGP, they have so far turned out be ambiguous. The existence of a high mass strangelet may serve as a signature for the existence of a QGP.

- **Astrophysical consequences** The first notion of the possible existence of stable SQM came from astrophysical motivations. It was first speculated that SQM might exist within the core of neutron stars [3]. Much interest has been spurred by the possible implications of the existence of strange stars. SQM was proposed as a dark matter candidate that might have been made in the early universe [4, 5].

- **Energy Source** Stable positive SQM has the unique property that it can grow to arbitrarily large \( A \). This is because SQM is almost neutral, so Coulomb effects are less destabilizing than in ordinary nuclear matter, and thus SQM with large masses is not subject to fission. One could grow positive SQM by bombarding it with slow neutrons. The neutrons would excite the SQM, which would subsequently decay into a more stable state, emitting a photon \((n + {}^A \text{S} \rightarrow {}^{A+1} \text{S}^* \rightarrow {}^{A+1} \text{S}' + \gamma)\). This could potentially be a clean, compact energy source [9].

- **New Physics** SQM would provide a new area for physics research. SQM is a many body system of quarks and gluons. The structure of this QCD system could be studied. Additionally, strange quark matter with large \( A \) can support a large number of electrons. Therefore, large \( Z \) systems could be studied.

See Refs. [6], [7], and [8] for reviews and further information on strange quark matter.

The remainder of this chapter consists of a survey of strangelet theory, strangelet production, and experimental searches for strangelets. The rest of the thesis focuses on an experimental search for strangelets (experiment BNL-E864).
1.1 Bag Model

The stability of strangelets has been calculated using the framework of the MIT Bag Model [10]. The Bag Model is motivated through considerations of the properties of the QCD vacuum [11]. First consider “empty” vacuum, in which there are no gluons, only zero-point fluctuations. [Zero-point fluctuations are quantum fluctuations around the lowest energy state in the gluon field.] Now imagine that we add a pair of gluons with opposite color charge and spin and an average separation of $r$. The energy is then given by:

$$E(r) = KE + V = \frac{A}{r} + \left( -C \frac{\alpha_c}{r} + kr \right)$$

(1.2)

where $A$ and $C$ are constants, $r$ is the separation between the two gluons, and $\alpha_c$ is strong force running coupling constant. The $\frac{1}{r}$ dependence in the kinetic energy for a pair of gluons can be seen simply by considering the uncertainty principle ($\Delta r \Delta p \geq \frac{1}{2} \hbar$). For the massless gluons $p = E$, and thus $E \propto \frac{1}{r}$. The $kr$ term is due to confinement.

For $r \ll R$ ($R$ is the length at which the coupling constant becomes large) $\alpha_c$ is small and $E(r)$ is positive. For $r \gg R$, $E(r)$ grows rapidly because single colored objects cannot exist in isolation. However, for an intermediate region where $r \approx R$, $E(r)$ can become negative. This implies that there exists a “true” QCD vacuum, which is at a lower energy than an empty vacuum. The QCD vacuum is then a random distribution of cells that contain a gluon pair in a color and spin singlet state. When quarks are added, gluons are displaced creating a region of empty vacuum. Therefore, quarks are confined to a bubble of radius $R$ of empty vacuum. The true vacuum exerts a pressure $B$ on the quarks which are in the empty vacuum. The radius $R$ adjusts itself so that the outward pressure of the quarks is balanced by the inward pressure of the true vacuum. This is the basis of the Bag Model.

If one takes the $u$ and $d$ quarks to be massless, there are four adjustable parameter in the Bag Model: bag pressure $B$, the mass of the strange quark ($m_s$), the quark-gluon coupling constants ($\alpha_c$), and the zero point energy ($Z_0$) associated with the quantum modes within the bag. This model has proved to be successful in predicting hadron masses. The parameters are determined by fitting to, for example, the masses
of $N, \Delta, \Omega, \omega$. The model then predicts the masses for the other hadrons. Typical Bag Model parameters which fit the hadron masses well are: $B^4 = 0.145$ GeV, $\alpha_c = 2.2$, $m_s = 0.280$ GeV, $Z_0 = 2.0$ [12].

The Bag Model has been used to estimate the binding energy of strangelets for both large and small systems.

### 1.1.1 Large Systems

Large systems ($A \gtrsim 100$) can be approximated by treating quark matter as a Fermi gas of particles in a bag.

Chin and Kerman [13] were the first to calculate the energy per baryon of strangelets within the framework of the Bag Model. They used systems where ($A > 100$) and took $B^{1/4} = 145$ MeV, $\alpha_c = 2.2$, and $m_s = 279$ MeV. They computed the minimum energy per baryon as a function of $f_s$, and found that bulk strange quark matter is metastable for $f_s > 0.8$, with the most stable system at $f_s \approx 1.8$. This would correspond to a charge to mass ratio $\frac{Z}{A} = \frac{(1 - f_s)}{2} = -0.4$ if $N_u = N_d$, where $N_u$ is the number of $u$ quarks, and $N_d$ is the number of $d$ quarks.

Farhi and Jaffe [14] also considered large systems. In addition to the standard Bag Model parameters, they included surface and Coulomb energy terms (for $A < 10^7$). They took a very low value of $\alpha_c = 0.6$. They argue that the the value of $\alpha_c$ which is derived from fitting light hadrons may not apply to systems with large $A$. This is because the mass, $\alpha_c$, and $B^{1/4}$ are coupled when fitting hadron spectra. In addition, the fits to the lighter hadrons include a fit to the zero point energy, which influences $\alpha_c$. They find that bulk strangelets are stable, but with a $Z/A$ ratio between 0.1 and 0.3. They show that as $\alpha_c$ increases, $f_s$ decreases due to the negative exchange energy of massive quarks. In bulk, where strangelets are the most stable, they find that $f_s \approx 0.81$, which corresponds to $\frac{Z}{A} = 0.095$.

### 1.1.2 Small Systems

Farhi and Jaffe [14] replace the Fermi gas by the hadronic bag model and populate the quark orbitals in a spherical bag in order to study the properties of systems
with $A \lesssim 100$, and use typical bag model parameters. For very low $A \leq 6$ they include the first order exchange energy term, and for the bag model parameters take $B^{1/4} = 145$ MeV, $m_s = 280$ MeV, $Z = 1.84$, $\alpha_c = 2.2$. Fig. 1.3 shows their results. The solid dots are the lightest non-strange multiquark matter system for a particular value of $A$, while the open circles are lightest strange multiquark hadrons with the number of strange quarks given in parenthesis. It can be seen that while the strange multiquark systems are more tightly bound than the corresponding non-strange multiquark systems, they are still unbound ($E/A > 939$ MeV), with the possible exception of the six quark state which is known as the H-dibaryon. For $A > 6$ they remove the $\alpha_c$ correction because it is too difficult to calculate and use the bag model parameters $B^{1/4} = 150$ MeV, $m_s = 150$ MeV, $Z = 2.0$, $\alpha_c = 0$. They find that strangelets will be metastable when $A \gtrsim 10$, and completely stable when $A \gtrsim 70$. See Fig. 1.4.

Gilson and Jaffe [15] performed a thorough study the stability of small strangelets by using the same method as Ref. [14]. They explore systems with $A < 100$ for
Figure 1.4: $E/A$ for strangelets with $A \leq 100$. From Ref. [14].

different values of $\varepsilon_b$ (the energy per baryon in bulk). They model the strangelet as a gas of noninteracting fermions confined to a bag and determine the energy eigenvalues by filling the energy levels of the bag. Taking $\alpha = 0$, they obey the Pauli Exclusion principle, minimize the energy (for each $A$) and adjust the bag radius so that the quark pressure balances the vacuum pressure $B$. They have the following free parameters: the energy per baryon in bulk $\varepsilon_b$, the mass of the strange quark $m_s$, and the baryon number $A$, and include surface and curvature effects. Fig. 1.5 shows their results for different values of $m_s$ and $B$. The species noted on the figure are stable against single baryon emission. See Sec. 1.2 for a discussion of the possible decay modes of strangelets. If one looks at the energy per baryon for the lightest systems, the values appear to be at odds with their previous calculations in Fig. 1.3.

Madsen [20] developed a mass formula for spherical lumps of three flavor quark matter. He derives the formula from an asymptotic expansion within the MIT bag model. He finds that the general structure of shell model results for strangelet systems can be explained by a liquid drop model mass formula that includes volume, surface, and curvature contributions. The curvature correction is the dominant contribution for $A < 100$, and it is destabilizing. The advantage of this procedure is that the
Figure 1.5: Energy per baryon as a function of A. (a) $\epsilon_b = 930$ MeV, $m_s = 150$ MeV, $B^{1/4} = 154.64$ MeV. (b) $\epsilon_b = 950$ MeV, $m_s = 150$ MeV, $B^{1/4} = 158.71$ MeV. (c) $\epsilon_b = 970$ MeV, $m_s = 150$ MeV, $B^{1/4} = 162.31$ MeV. (d) $\epsilon_b = 950$ MeV, $m_s = 250$ MeV, $B^{1/4} = 151.60$ MeV. The species noted by dark dots are stable against single baryon emission. From Ref. [15].
Figure 1.6: The smooth curves are for the liquid drop model, while the jagged curves are for the associated shell model calculation. The plot uses $B^{1/4} = 145$ MeV, and $m$, ranges from 50 to 300 MeV in steps of 50 MeV (bottom to top), while the plot on the right uses $B^{1/4} = 165$ MeV, and $m$, ranges from 50 to 350 MeV in 50 MeV steps. From Ref. [20].

Calculations are much easier to perform than shell model calculations. See Fig 1.6. The shell model calculations are done by the same procedure as Gilson and Jaffe except that no zero-point correction was applied.

1.2 Stability of Strangelets

1.2.1 Stability Conditions

Strangelets would be completely stable if their energy per baryon is smaller than that of nuclear matter. This can be written as follows:

$$\frac{E}{A} < m_N - \epsilon_B$$

(1.3)
where $E/A$ is the energy per baryon of the strangelet, $m_N$ is the mass of the nucleon, and $\epsilon_B$ is the binding energy per nucleon of the nuclear system with baryon number $A$.

Strangelets are metastable when they are more tightly bound than the corresponding baryonic matter, but less bound than nuclear matter: a strangelet with $f_s = 1$ would need to have a lower $E/A$ than that of a $\Lambda$; a strangelet with $f_s = 2$ would need to have a lower $E/A$ than that of a $\Xi$; and a strangelet with $f_s = 3$ would need to have a lower $E/A$ than that of a $\Omega$. If strangelets were less tightly bound than their corresponding baryon, than an assembly of $\Lambda$, $\Xi$, or $\Omega$ particles would be formed rather than a strangelet. The stability conditions for metastable strangelets can be summarized as follows:

$$\frac{E}{A} < f_s m_\Lambda + (1 - f_s) m_N - \epsilon_B \quad \text{when} \quad 0 \leq f_s < 1 \quad (1.4)$$

$$\frac{E}{A} < (f_s - 1) m_\Xi - (2 - f_s) m_\Lambda \quad \text{when} \quad 1 \leq f_s < 2$$

$$\frac{E}{A} < (f_s - 2) m_\Omega - (3 - f_s) m_\Xi \quad \text{when} \quad 2 \leq f_s < 3$$

Metastable strangelets could decay via the weak process.

### 1.2.2 Decay Modes of Strangelets

If strangelets ($S$) are not completely stable, they will decay. Depending on what is energetically favorable, a strangelet could possibly be subject to the following decays [16]:

- **Strong Neutron Emission ($S \to S' + N$)** The decay has the properties $\Delta A = -1$, $\Delta Y = -1$, and $\Delta Z = 0$, where $Y = B + S$ is the hypercharge, where $B$ is the baryon number and $S$ is the strangeness. This proceeds at a rate typical of strong interactions (corresponding to $\approx 10^{-22} s$). The corresponding proton emission is similar, but suppressed due to the Coulomb barrier.
• **Strong $\alpha$ Decay ($S \rightarrow S' + \alpha$)** The decay has the properties $\Delta A = -4$, $\Delta Y = -4$, and $\Delta Z = -2$. Because $\alpha$ particles have large binding energy per baryon, it is energetically favorable for a wide range of strangelets. However, this process is expected to be inhibited for two reasons: (1) it is suppressed due to the Coulomb barrier; (2) the quarks in a strangelet are bound differently from a nucleon, and thus the overlap of the wave function of $u$ and $d$ quarks and the wave function of an $\alpha$ particle is small.

• **Weak Neutron Emission ($S \rightarrow S' + N$)** This decay has the properties $\Delta A = -1$, $\Delta Y = 0$, and $\Delta Z = 0$. This process is much slower than strong neutron emission because it is a weak process and it includes the Cabibbo suppression factor $|V_{us}|^2$. Dover [19] has estimated a characteristic decay rate corresponding to approximately $5 \times 10^{-9}$ sec. Here is an example of a strangelet decaying via weak neutron emission:

```
\begin{array}{c}
  s \\
  u \\
\end{array} \quad \quad \begin{array}{c}
  d \\
  u, d \\
\end{array}
```

• **Weak Pion Decay ($S \rightarrow S' + \pi$)** A strangelet can emit a pion via a strangeness changing weak interaction. This decay has the properties $\Delta A = 0$, $\Delta Y = \pm 1$, and $\Delta Z = \pm 1$. The decay rate would be similar to weak neutron emission. Here is an example of a strangelet decaying via weak pion decay:

```
\begin{array}{c}
  \bar{u}, u \\
  W \\
\end{array} \quad \quad \begin{array}{c}
  d, \bar{d} \\
  s \\
\end{array}
```

• **Weak Radiative Decays ($S \rightarrow S' + \gamma$)** This decay has the properties $\Delta A = 0$, $\Delta Y = \pm 1$, and $\Delta Z = 0$. Weak radiative decays applies to excited strangelets, and results in a more stable strangelet. The decay rate is suppressed by a factor of $\alpha_{em} \approx \frac{1}{137}$ compared to weak neutron emission, and corresponds to about $10^{-6}$ sec.
- **Weak Semileptonic Decays** \((S \rightarrow S' + e + \nu)\) This decay has the properties \(\Delta A = 0\), \(\Delta Y = \pm 1\), and \(\Delta Z = \pm 1\). This process is suppressed due to the three-body phase space kinematics. A decay rate corresponding to approximately \(10^{-4}\) sec has been estimated [9].

---

**Experimental Consequences**

The current round of experimental searches for strangelets in heavy ion colliders require the strangelet to travel \(\gtrsim 100\) ns in the lab, or \(\gtrsim 40\) ns in the strangelets frame of reference, in order to be detected. Therefore, current experiments should be sensitive to strangelets which decay via weak radiative decays or weak semileptonic decays. However, they may have only limited sensitivity to strangelets which decay via weak neutron emission or weak pion decay.

Berger and Jaffe [16] developed a mass formula to study the stability of strangelets near flavor equilibrium. They expand the energy \(E(A, Y, Z)\) of a strangelet of baryon number \(A\), hypercharge \(Y\), and electric charge \(Z\) around the energy minimum:

\[
E(A, Y, Z) \sim \varepsilon_0 A + \frac{1}{2} \Delta_Y (Y - Y_{\text{min}})^2 + \frac{1}{2} \Delta_Z (Z - Z_{\text{min}})^2 + 4 \pi \sigma R^2
\]

(1.5)

where \(\varepsilon_0\) is the energy per baryon number in bulk \((A \rightarrow \infty)\), \(\Delta_Y\) and \(\Delta_Z\) are curvatures at the minimum in \(Y\) and \(Z\), \(\sigma\) is the strangelet surface tension, and \(R\) is the strangelet radius. (Note that a factor of two error in their surface energy term was corrected in an erratum [16].) They rewrite this formula so that there are only two parameters:
Figure 1.7: Strangelet stability as a function of $Y$ and $A$ for fixed $\epsilon_0 = 930$ MeV, $m_s = 150$ MeV/c$^2$, and $Z = Z_{\text{min}}$. Strong neutron decay occurs in region I, weak neutron decay occurs in region II, and region III is stable against both types of neutron decay. From Ref. [16].

$\epsilon_0$ and $m_s$, and use it to determine the stability of strangelets in $A$, $Y$, and $Z$ space for choices of $\epsilon_s$ and $m_s$. Fig. 1.7 shows the stability against strong neutron emission and strong $\alpha$ emission for $\epsilon_0 = 930$ MeV, $m_s = 150$ MeV/c$^2$, and $Z = Z_{\text{min}}$. Strong neutron decay occurs in region I, weak neutron decay occurs in region II, and region III is stable against both types of neutron decay.

Shaw et al. used this mass formula to investigate the stability of strangelets against strong and weak neutron decay. Fig. 1.8 shows the stability against neutron emission by the strong and weak interactions for $A = 15$ strangelets for $m_s = 150$ MeV/c$^2$ with different values of $\epsilon_0$. Strangelets are stable against strong neutron decay for $(Y, Z)$ left of the solid line for a particular $\epsilon_0$. The shaded area shows the region which is unstable against weak neutron decay for $\epsilon_0 = 925$ MeV. The shaded region grows as $\epsilon_0$ gets larger, and disappears for $\epsilon_0 \leq 920$ MeV. The black dot, which is located at $(4,1)$ corresponds to the most stable $A = 15$ strangelet.

Therefore, there exist regions in $(A,Y,Z)$ space where strangelets are stable against both strong and weak neutron decay. Strangelets in these regions would live long
Figure 1.8: Regions in \((Y,Z)\) phase space that allow weak and strong neutron decays for \(A = 15\) strangelets. See text for details. From Ref. [9].

enough to be detected by current experiments.

1.3 Production Models

There are three classes of strangelet production models: QGP, coalescence, and thermal models. The first class of models require the existence of a QGP. The QGP goes through the process of "strangeness distillation" and radiates off antistrangeness and cools into a strangelet. The second class are coalescence models. In these models, strangelets are built up from the hyperons and nucleons created in the interaction. When two baryons are close enough to each other in momentum and position space, they can be coalesced. The third class are thermal models, in which thermal and chemical equilibrium are assumed.

1.3.1 Quark Gluon Plasma Models

QGP based production models predict that strangelet cross sections may be rather large.
QGP Formation

The first requirement to create a strangelet from a QGP is for the QGP to be formed in the first place. To date, there is no conclusive evidence that a QGP is being formed at either AGS (the Alternating Gradient Synchrotron at Brookhaven National Laboratory) or SPS (Super Proton Synchrotron at CERN) energies. However, recently it has been predicted by Kapusta et al., and Werner that that a QGP may be produced occasionally at AGS and SPS energies.

Kapusta et al. [24] start with the conjecture that the energy densities achieved at the AGS are high enough to be in the QGP region of the phase diagram. The system is then in a superheated state. Fluctuations in the free energy can then provide the seed necessary to make the phase transition to a QGP. If the average energy density in the surrounding space is above a certain critical value, then the plasma droplet will grow rapidly. Taking a simple dynamical picture assuming complete stopping, a simple model of the hadronic equation of state, and assuming that the phase transition to a QGP is first order (the first derivative of the free energy is discontinuous), they study the nucleation rate of plasma droplets in superheated hadronic matter and the growth velocity of the droplets. They find that a QGP may be nucleated from hadronic matter as often as one in a hundred or one in a thousand central collisions. It is important to note that they take a simple geometry picture of the QGP as a sphere. For higher energy systems, such as those at the SPS, other geometric contributions become important.

Werner [25] focuses mainly at SPS energies, and investigates the formation of QGP droplets due to geometrical fluctuations. He takes a percolation approach to finding high density domains for the final stage of nucleus-nucleus collisions, and treats them as QGP droplets. This approach allows the inclusions of of all geometrical contributions. He finds that occasionally the energy densities are large enough to form QGP droplets.
QGP Cooling into a Strangelet

Liu and Shaw [26] computed strangelet cross sections assuming that a QGP was formed in the collisions. In their model, the strangeness of the QGP is charged up by fragmentation and recombination of quarks in a baryon-rich QGP:

- **Fragmentation** Quarks near the surface of a QGP can create $q\bar{q}$ pairs which radiate away from the QGP as mesons. Because this process is initiated by only one $u$ or $d$ quark, the other quark will "fall" inside the QGP. This tends to charge up the QGP because some of the time (they estimate 1/5) it will be an $s$ quark which falls into the QGP. See [26] for further details.

- **Recombination** More $\bar{s}$ quarks will radiate away from a QGP in the form of mesons than $s$ quarks because it is much easier for a $\bar{s}$ quark to find a $u$ or $d$ quark than for a $s$ quark to find an $\bar{u}$ or $\bar{d}$ in a baryon rich environment.

Their results depend strongly on the parameters, although in all cases they are much higher than corresponding coalescence calculations. They computed that the probability that an $A = 32$ strangelet resulted from collision of two sulphur nuclei to be between $8.8 \times 10^{-1}$ and $6.4 \times 10^{-7}$ per QGP.

Crawford *et al.* [27], as a continuation of the work of Liu and Shaw, made rough estimates of the production and lifetimes of strangelets as a function of $A$, $S$ and $Z$. Using an assortment of assumptions, they conclude that high sensitivity experiments could detect $A \sim 30$ strangelets.

Greiner *et al.* [28] study a mechanism of distillation for a separation between strangeness and antistrangeness in the QGP to hadronic matter phase transition. Once a QGP is formed, it will cool off by emitting mesons. $\bar{s}$ quarks will preferentially find $u$ and $d$ quarks to form $K$ mesons in a baryon rich plasma. The QGP charges up with strangeness relative to antistrangeness when the mesons are emitted by the plasma. After hadronization, a strangelets or an assembly of hyperons would be formed, depending on the bag model parameters. They assume that the QGP transition is first order. A schematic illustration of strangeness distillation is shown in Fig 1.9.
Figure 1.9: Schematic picture of strangeness distillation. (a) Kaons are radiated from the QGP, charging the up QGP with strangeness; (b) As the QGP cools, Kaons are radiated from the QGP-HG (where HG is a hadron gas) coexistence region further charging the QGP up with strangeness; (c) After hadronization, a strangelets or an assembly of hyperons would be formed, depending on the bag model parameters. From Ref. [28].
Figure 1.10: Baryon number and strangeness content evolution for different values of the initial strangeness fraction. The initial conditions are $A = 100$, $S/A = 10$, $B^{1/4} = 145$ MeV, where $S/A$ is the initial entropy per baryon number. From Ref. [29].

Greiner and Stöcker [29] further expand on their model. They now take into account the emission and reabsorption of pions, nucleons, and strange particles from the surface of the hadronic fireball prior to the formation of the QGP. This would then give the QGP an initial strangeness fraction $f_s(t = 0)$ before it would go through the QGP-HG phase transition where it would further charge up due to the strangeness distillation discussed in Ref. [28]. They then calculate the baryon number of the QGP as a function of time for different values of the initial $f_s$ (strangeness fraction just before the QGP-HG phase transition.) A strangelet of size $A$ would then be formed. In Fig. 1.10 they start off with a QGP with $A = 100$, and watch the baryon number and strangeness fraction evolve for different values of the initial strangeness fraction (ranging from 0 to 1.5). A strangelet with $A_B^{QGP}$ and $f_s^{QGP}$ at large times would then be formed. This model favors the formation of strangelets with $f_s \sim 1.2 - 2$, which would correspond to $Z/A \sim (-0.1) - (-0.5)$. 
1.3.2 Coalescence

The coalescence picture for the formation of ordinary non-strange nuclei is well established at BEVALAC energies [17]. An extension of this picture to strange nuclei and AGS energies was performed by Dover [18]. The number of clusters $N(A, S)$ of baryon number $A$ and strangeness $S$ produced per collision can be written as:

$$N(A, S) = \frac{N(A, S) N(A, 0)}{N(A, 0)} N_\alpha \approx \lambda |S| P^{A-4} N_\alpha$$  \hspace{1cm} (1.6)

The addition of one non-strange baryon to a cluster incurs a penalty factor $P$, while the conversion of a non-strange quark to a strange quark ($u, d \rightarrow s$) at fixed $A$ leads to a penalty factor $\lambda$. Estimates for $\lambda$, $P$, and $N_\alpha$ have been made by Baltz at al. [21]. They determine $P \approx \frac{1}{25}$, $\lambda \approx 0.3$, and $N_\alpha = .018$ per central interaction. Experiment E864 will make detailed measurements of light nuclei. These coalescence measurements will allow for quantitative predictions of strange quark matter via coalescence.

Thermal Model

A fireball model based on the assumption of thermal and chemical equilibrium has been used to make predictions for strange matter production in Au+Au collisions at AGS energy [22]. The thermal model predicts somewhat smaller production probabilities compared to the coalescence model for multi-strange clusters with baryon number larger than 4.

1.3.3 Production Formula

Because experiments measure only a limited region of phase space, strangelet production models are needed to convert measurements into cross sections. A reasonable model for the differential cross section would be that the strangelet production has a gaussian shape in rapidity $y$ and an exponential shape in transverse momentum ($p_t$) [23], where $y$ and $p_t$ are taken to be uncorrelated. In other words, it is assumed
that \( \frac{d^2N}{dydp_t} \) factorizes:

\[
\frac{d^2N}{dydp_t} \propto p_t e^{-\frac{2p_t}{<p_t^2>}} e^{-\frac{(y-y_{cm})^2}{2\sigma_y^2}}
\]  

(1.7)

where \(<p_t>\) is the mean transverse momentum, \(y_{cm}\) is the center-of-mass rapidity, and \(\sigma_y\) is the standard deviation of the rapidity distribution of the strangelet. A further complication is that \(<p_t>\) and \(\sigma_y\) may have a dependence on \(A\).

One general feature of most models is that the mean transverse momentum of the produced strangelets scale as \(\sqrt{A}\) (\(<p_t> = k\sqrt{A}\)). For example, in the coalescence model the final transverse momentum is a result of a series of transverse momentum impulses due to the accreted constituents. In each impulse only a limited range of momentum can be accreted. The mean transverse momentum can then be modeled as a "random walk" process of the accretion of baryons. The RMS distribution for a random walk is given by \(L\sqrt{N}\), where \(L\) is the step length, and \(N\) is the number of steps. In this case, \(L\) is the momentum of the typical baryon, and \(N\) is the baryon number \(A\). Thus, \(<p_t> \propto \sqrt{A}\). A constant value of approximately 0.6 GeV/c is reasonable (this is a typical mean \(p_t\) of produced baryons), so \(<p_t> = 0.6\sqrt{A}\) GeV/c is a popular model.

The \(\sigma_y\) term may also have an \(A\) dependence in an accretion picture. The probability of accreting another hadron of rapidity \(y\) is proportional to \(\frac{dN}{dy}\), and thus the growing strangelet must be able to find another hadron with an appropriate \(y\). This tends to narrow the \(y\) distribution for larger \(A\). One common model used is one with a \(1/\sqrt{A}\) dependence (\(\sigma_y \propto 1/\sqrt{A}\)). A constant value of approximately 0.5 is reasonable (this is a typical of the gaussian rapidity width of produced baryons), so \(y = 0.5\), or \(y = 0.5/\sqrt{A}\) are popular models.
Figure 1.11: Chart of stable and metastable isotopes up to Ne. The black dots correspond to nuclei with $Z/A \leq 0.3$.

1.4 Experimental Approach

1.4.1 Heavy Ion Collisions

The most likely environments to create strangelets in the laboratory are in heavy ion collisions. If the strangelets are produced by coalescence, the large strange particle production in heavy ion collisions provide adequate building blocks to form strangelets. If they are produced by a QGP, heavy ion collisions are the most likely to have a high enough temperature and density to form a QGP.

An experimental signature for strangelets is a particle with a low $Z/A$ ratio. For example, a $Z=1, M=30$ ($Z/A = 0.033$) strangelet is plausible. The only known physics background with large baryon numbers and $Z/A < 0.3$ are nuclei with an anomalously large neutron content. See Fig 1.11 for a chart of stable and metastable isotopes from hydrogen to Ne. The black dots correspond to nuclei with $Z/A \leq 0.3$. 
1.4.2 Experimental Searches for Strangelets

To date, the searches for strangelets have consisted of experiments which look for particles with low charge to mass ($Z/A$) ratios. If such an object was discovered, a follow-up experiment would be required to study the properties of the object.

In most strangelet searches, two general classes of spectrometers have been used: focussing spectrometers, and open geometry spectrometers.

Most previous strangelet searches have used focussing magnetic spectrometers. Magnetic spectrometers select (or accept) only those particles in a small region of phase space. The spectrometer magnets are set to accept a particular (and narrow) range of magnetic rigidities (rigidity is defined as the ratio of momentum to charge: $R \equiv p/Z$). Because of the small acceptance, the results become extremely model dependent for different rigidities (or masses). Therefore, search experiments require a number of rigidity settings. However, the rigidity coverage of these spectrometers is limited by the strength of the magnets. Above the maximal rigidity setting, the results become extremely model dependent because the acceptance is not peaked at the center-of-mass rapidity. Experiments E878, E886, and NA52 are all focussing spectrometers.

Open geometry spectrometers have a relatively large acceptance, and measure around the center-of-mass rapidity. Therefore, searches for a large range of $Z/M$ can take place simultaneously. E814, which conducted the first search for strange quark matter, was such a spectrometer. Experiment E864, which is the topic of this thesis, also employs a large acceptance open geometry spectrometer.

E814

BNL experiment E814 [1, 30] conducted the first search for strangelets in heavy ion collisions. E814 looked at collisions between 14.6 GeV/c per nucleon $^{28}$Si ions and a Cu target. E814 is a magnetic spectrometer that consisted of two dipole sweeping magnets, drift chambers, a scintillator hodoscope, and a hadronic calorimeter. The apparatus was sensitive to particles with $Z/M$ ratios between 0.1 and 0.3 (GeV/c$^2$)$^{-1}$ within $\pm 0.5$ units of center-of-mass rapidity.
Figure 1.12: Results from E814: 90% confidence level limits for positively charged strangelet production in 14.6 GeV/c Si+Cu collisions. From Ref. [30].

No positively charged strangelets were observed. The upper limits on strangelet production are shown in Fig. 1.12. These limits assumed the production formula given from Eq. 1.7, with \( \langle p_t \rangle = 0.7\sqrt{A} \) GeV/c, \( y_{em} = 1.49 \), \( \sigma_y = 0.5 \). Because the E814 spectrometer had acceptance around central rapidity and acceptance over a broad range of \( p_t \), the limits varied by no more than a factor of two when varying \( \langle p_t \rangle \) from \( 0.5\sqrt{A} \rightarrow 0.9\sqrt{A} \) and varying \( \sigma_y \) from 0.5 to 0.7.

Strangelets produced at center-of-mass rapidity would need to live 50 ns in their frame to be detected in the E814 calorimeter, which is 36 m downstream of the E814 target.

E878

E878 [31] is a double focussing spectrometer which has a geometrical acceptance of 200 \( \mu sr \) centered about zero degrees, scintillation counters for charge and time-of-flight measurements, Čerenkov counters to help with particle identification, and drift chambers for momentum analysis. The spectrometer was operated at a number of fixed rigidities ranging from +15.0 GeV to -20.0 GeV. E878 searched for both
positive and negative charge 1 and 2 strangelets in 10.8 GeV/c per nucleon Au+Au collisions. For particles species with $A>8$ E878 no longer measures at mid-rapidity, so the sensitivity of their measurements becomes extremely model dependent. No strangelets were found in the data [31]. Figs. 1.13 and 1.14 show the upper limits for strangelet production for states with $Z=\pm 1$ and $Z=\pm 2$ for three different parameters in the production formula given in Eq. 1.7. Strangelet predictions of Crawford et al. [27] are shown as triangles and hypernuclei predictions of Baltz et al. [21] are shown as squares. In Figs. 1.13 and 1.14 they show their sensitivities for three different choices of $\sigma_v$: (1) $\sigma_v = 1.0/\sqrt{A}$, (2) $\sigma_v = 0.5/\sqrt{A}$, and (3) $\sigma_v = 0.5$. They take $<p_t> = 0.6\sqrt{A}$ GeV/c, $y_{cm} = 1.6$. Their acceptance improves slightly with decreasing $<p_t>$.

Strangelets produced at center-of-mass rapidity to live 100 ns in their frame to be detected in the E878 apparatus.
Figure 1.14: Results from E878: 90% confidence level limits for negative strangelet production in 10.8 GeV/c Au+Au collisions. From Ref. [31].

**E886**

E886 [32] is a focusing spectrometer with a beam line which can transport rigidities \(\frac{p}{Z}\) up to 2.0 GeV. The beam line was originally built to provide up to 2 GeV/c kaons for H-search experiments. The angular acceptance is \(\Delta \Theta = \pm 0.005\) rad that was centered at 0.099 rad relative to the beam direction. The kinematic acceptance of the spectrometer is limited to relatively low rapidities \((y < 0.6)\), and the rapidity acceptance is very narrow \(< 0.5\) units). Depending on the A of the strangelet, the spectrometer has a 1 to 5% acceptance over a range of \(p_t\) from 0.1 – 0.9 GeV/c. E886 looked at 10.8 GeV/c per nucleon Au+Pt collisions. E886 saw no strangelet candidates [32]. The upper limits on strangelet production are shown in Fig 1.15. These limits assumed the production formula give from Eq. 1.7, with \(\sigma_y = 0.5\), and \(<p_t> = 0.6\sqrt{A}\) GeV/c. These results are extremely model dependent. For example, if \(\sigma_y \propto 1/\sqrt{A}\) the detector has very little acceptance.
Figure 1.15: Results from E886: 90% confidence level limits for positively charged strangelet production in 10.8 GeV/c Au+Pt collisions. From Ref. [32].

NA52

NA52 [33] is a double focussing spectrometer which has a geometrical acceptance of 4 μsr, consisting of scintillation counters for charge and time-of-flight measurements, wire chambers to improve the momentum resolution and provide charged-particle tracking through the spectrometer, and a hadronic calorimeter to make a second mass measurement. NA52 runs two positive and negative rigidity settings of ±100 GeV and ±200 GeV. This permits mass measurements in the range of 10 GeV/c² < M/Z < 40 GeV/c². NA52 looks at 157.7 GeV/c per nucleon Pb+Pb collisions at CERN. NA52 put limits on strangelet production for their first (Fall 1994) run [33]. Fig. 1.16 shows the experimental upper limits for strangelet production. As illustrations, NA52 shows three different production models for < p_t >: < p_t > = 0, < p_t > = 0.1√A, < p_t > = 0.5√A. NA52 measure at < p_t > = 0, so this line shows there best possible limits in an unphysical case. The line with < p_t > = 0.5√A is the one most directly comparable to other experiments.

Strangelets produced at center-of-mass rapidity would need to live 130 ns in their frame to be detected in the NA52 apparatus.
Figure 1.16: Experimental upper limits for positive (lower lines) and negative (upper lines) strangelet production assuming different mean transverse momenta. From Ref. [33].

1.5 Thesis Goals

In this thesis I describe experiment E864, which is a new experiment designed to search for strange quark matter. The two main goals of the thesis is to perform the first search with the E864 apparatus, and evaluate the detector's performance in order to gain insight as to whether the experiment will be able to reach its ultimate sensitivity levels.
Chapter 2

The Experiment

This chapter contains an overall description of the E864 experiment. The following three chapters contain the detailed design of some of the components of the E864 apparatus. This thesis is derived from the analysis of data from the 1994 run of E864 experiment at the Brookhaven Alternating Gradient Synchrotron. The first half of the 1994 run, which was the first E864 run, was used to commission the detector, while the second half was used to take physics data. The complete detector was not installed for this 1994 run and, therefore, along with the description of the design of the complete detector I indicate what was in place for the first run.

2.1 Experimental Approach

An experimental signature for strangelets is an anomalously low charge to mass ratio with the production peaked at the center-of-mass velocity (the rapidity $y$ is defined as $y = \frac{1}{2} \ln[(E + p_z)/(E - p_z)]$, $E$ is the energy and $p_z$ is the longitudinal momentum.) Other than several known neutron-rich isotopes, there is no known physics background. AGS E864 was designed with the goals of the strangelet search in mind. A open geometry, large acceptance spectrometer which measures particles produced in the center-of-mass rapidity was chosen because it leads to an efficient search with minimal model dependence.

The experiment has a large acceptance, high rate capability, excellent resolution,
and good background rejection. [By background rejection we mean the ability to
discriminate real high mass particles with particles which are incorrectly reconstructed
to have a higher mass than they actually have.] It is designed to utilize the heaviest
ions produced by the AGS ($^{197}\text{Au}$) in order to have the highest probability of produc-
ing rare high mass objects. The beam momentum for the 1994 run was 11.6 GeV/c
per nucleon.

The mass ($M$) of a particle can be reconstructed if one knows its rigidity ($R = \frac{p}{Z}$,
where $p$ is the momentum), charge ($Z$), and velocity ($\beta = \frac{v}{c}$, $\gamma = \frac{1}{\sqrt{1-\beta^2}}$):

$$M = \frac{p/Z}{\gamma \beta} = \frac{R}{\gamma \beta} Z$$ (2.1)

The rigidity of tracks which originate in the target can be reconstructed with the
use of the known magnetic fields and the knowledge of the slope and intercept of the
track downstream of the magnets.

The spectrometer (see Figs. 2.1 and 2.2) is comprised of two dipole magnets (M1
and M2), three highly segmented scintillation counter hodoscopes (H1, H2, and H3),
three straw tube wire tracking chambers (S1, S2, and S3), and a spaghetti calorimeter
(CAL). All the detectors are located below the plane of the beam and target. The
fiducial region of the detectors cover a horizontal angular range from 171 mr to −32 mr
(from the bend side of the neutral line to the non-bend side) for neutrals, and a vertical
angular range from −17.5 mr to −51.3 mr. Our furthest downstream detector, the
calorimeter, is located 27.5 m downstream of the target, and is 5.8 m long by 1.3 m
high. The open geometry design allows us to have a detector that has a good
acceptance both around central rapidity and in transverse momentum. This large
acceptance minimizes our sensitivity to production models, however, it also makes us
vulnerable to backgrounds. Therefore, the detector is highly segmented and allows
for redundant measurements in order to reject backgrounds at a sufficient level.

A large vacuum vessel encompasses the beam, beam fragments, and the peripheral
products. The vacuum is necessary because the gold ions would interact in air,
showering the detectors with background hits. The detectors are placed immediately
under the vacuum chamber in order to measure to the lowest transverse momentum
($p_t$) possible. This poses a physical constraint on the hodoscope system and has an
Figure 2.1: The plan and elevation views of the 1994 configuration of the E864 detector, in which the detector was partially installed. M1 and M2 are the dipole spectrometer magnets; H1, H2, and H3 are the scintillation counter hodoscopes; S2, and S3 are the straw tube arrays; CAL is the calorimeter.
Figure 2.2: Perspective view of the 1994 configuration of the E864 detector, in which the detector was partially installed. M1 and M2 are the dipole spectrometer magnets; H1, H2, and H3 are the scintillation counter hodoscopes; S2, and S3 are the straw tube arrays; CAL is the calorimeter.
impact on the system’s design and performance.

The two dipole magnets are set to different field values for different physics topics. The settings of the magnets optimize the acceptance for different values of the charge to mass ratio \((M/Z)\). The majority of the E864 running occurs at four different field settings:

1. \(M1=M2=\text{"+1.5T"} \) Positive Strangelet Search \((Z/A \lesssim 0.3)\)
2. \(M1=M2=\text{"+.75T"} \) Light Nuclei Studies \((Z/A \approx 0.5)\)
3. \(M1=M2=\text{"-.45T"} \) Anti-proton Measurements \((Z/A \approx -1.0)\)
4. \(M1=M2=\text{"-.75T"} \) Anti-deuterons and Negative Strangelet Search \((Z/A \gtrsim -0.67)\)

The field values are in quotes, because they are run at only approximately these field values. The magnets can be operated at different values for other physics topics, and \(M1\) and \(M2\) can be run with different field settings.

The three scintillation counter hodoscopes give space, time, and charge measurements. They are segmented in the horizontal direction to give horizontal position resolution and acceptable occupancy. The vertical position is derived from the time difference between the signals from the phototubes, which reside on the top and bottom of each hodoscope slat. The space points determine a rough slope and intercept of the downstream track. The time resolution of the hodoscopes is designed to resolve particle species which are up to at least half a unit above central rapidity. In fact, the resolution is good enough to resolve tracks with even higher rapidities. The pulse height spectrum, which is a measurement of the energy deposited of an ionizing particle traversing a scintillator slat, is proportional to the \(Z^2\) of the ionizing particle. The three charge measurements allows one to reconstruct the charge of the track to a high accuracy. Thus, by themselves the hodoscopes give excellent tracks in space and time with redundant measurements to reduce the chances of constructing an incorrect track.

The three arrays of straw tubes provide a high resolution position measurements, leading an improved determination of the rigidity (and thus mass) of the particle.
The first straw tube chamber (S1) is particularly important in rejecting background which does not originate from the target. This chamber was not installed for the 1994 run.

The spaghetti design calorimeter has excellent time resolution, good energy resolution, good spatial resolution, and a high rate capability. Independent of the tracking chambers, the calorimeter provides us with an additional mass measurement, giving us further rejection against background. Only one quarter of this detector was installed for the 1994 run.

Our trigger system is capable of selecting central interactions (those with the lowest impact parameters). At least at the AGS, strangelets are most likely to be formed (whether in a QGP or by coalescence) in the hottest possible environment. A beam counter (MITCH) provides timing information and trigger gating, and an interaction counter (MULT) provides a measurement of the centrality of interactions in the target. For future runs of the experiment, a second level trigger, selects on the energy and time of particles which strike the calorimeter. This is a selection on the rough mass of the particle. The "late energy" trigger (LET) is used to select high mass objects.

The desire to have a high rate experiment and large acceptance spectrometer requires a data acquisition (DA) system with the capability to record at a high data rate. The E864 DA system is designed to handle 4000 events per spill (with an event size of 6000 bytes, and a spill lasting one second long occurring every 4 seconds). The DA recorded approximately 1800 events per spill during the 1994 run. The event size was approximately 3500 bytes.

For the purposes of this thesis I define the following coordinate system:

- **x** – **horizontal direction** The acceptance is toward positive x.

- **y** – **vertical direction** The detector, which is below the beam, is in the negative y direction.

- **z** – **beam direction** The beam moves in the positive z direction.
Table 2.1: Minimum quality beam requirements at the E864 target.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Limit</th>
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</thead>
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<tr>
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</tr>
<tr>
<td>vertical size (full size)</td>
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</table>

2.2 Beam

The E864 detector is located in the A3 line of the AGS at Brookhaven National Laboratory (BNL). Prior to 1994 the A3 line transported only secondary beams of rigidity less than the primary beam, so we redesigned the beam tune to provide an acceptable primary beam at the E864 target. Two quadrupole magnets, a dipole magnet and a 4-jaw collimator were added to transport a beam with acceptable size and divergence requirements at the E864 target.

Monte Carlo studies of the E864 detector determined the E864 beam spot requirements. The E864 mass resolution degrades for spot sizes > 0.5 cm², and becomes unacceptable for spot sizes > 1 cm². Thus, it is desirable to have a spot size as close to 0.5 cm² as possible. In addition, the physical layout of the vacuum chamber and collimator require a small divergence (particularly in the vertical direction). The E864 beam requirements are summarized in Table 2.1. (Note that the beam sizes are the 2.5 σ full sizes at the target.)

Details of the beam design are presented in chapter 3.

During 1994 run the horizontal spot size was approximately 2 mm × 5 mm (y × z), the a vertical divergence was ±2 mr, and a horizontal divergence was ±1 mr. These are all well within our specifications. The majority of the "B=+1.5T" data was taken at a beam rate of ≈ 5 × 10⁵ gold ions per second.
2.3 Vacuum Chamber, Magnets, Collimator, and Plug

2.3.1 Vacuum Chamber

The E864 vacuum chamber is designed so that the Gold beam and a large fraction of its peripheral interaction products remain in vacuum until after the calorimeter. This is necessary because interactions and knock on electrons ($\delta$-rays) that a gold ion produces when traversing air would shower the detectors with background particles.

The desire to run the E864 spectrometer magnets at different field settings requires the $x$ dimension of the vacuum vessel to be large. A minimum beam clearance of 4 mr plus 0.5 cm (the beam size) is given in the $y$ direction.

The detectors downstream of the magnets reside below the vacuum chamber. Just downstream of M2 is a vacuum chamber section which includes a thin vacuum window, which is made out of Mylar and Kevlar. This window is just downstream of the second magnet. The particles we study go through the vacuum window, while the beam particles and fragments proceed down the vacuum chamber. A second vacuum chamber window is located downstream of the calorimeter and before the beam dump.

The vacuum chamber sections in the region of the magnetic field are constructed of aluminum, while the downstream section are made of steel.

2.3.2 Plug

The vacuum chamber lower wall, ribs, and bottom flanges increase the amount of material with which the particles produced at the target can interact. This leads to a large number of hits in the detectors from particles which do not come from the target. This had been studied by Monte Carlo programs prior to the 1994 run. A suitably designed plug can reduce this background. However, due to time and money constraints, the plug was not designed or fabricated for the first run. Thus, the detector occupancies for the 1994 run were quite high.

By comparing the data from the first run with Monte Carlo simulations of the detector, a plug was designed and installed for the 1995 run. The plug resides between
M1 and M2 and shields the vacuum chamber lower wall, ribs, and flanges. Fig. 2.3 shows the location of the plug relative to the target, M1, and M2. See chapter 4 for the design of the plug including comparisons between the data and Monte Carlo with the plug are presented.

2.3.3 Magnets

The E864 spectrometer uses two magnets, separated by 4 meters. The first magnet (M1) is a standard AGS 18D72 (18 inch width, 72 inches long dipole magnet, and a 8 inch gap – which we widened from 6 inches). The second magnet (M2) is a large aperture dipole obtained from SLAC (a 72D36). The two magnet system was arrived at in order to help reject backgrounds which do not come from the target. For example, the decay of the $\Lambda^0 \rightarrow p\pi^-$ can be reconstructed as a higher rigidity particle in a one magnet spectrometer system (unless one had an extremely long magnet), because the $\Lambda$ will not bend in the magnetic field. The separation of the two magnets also allows us the addition of a straw tube tracking chamber in between the two magnets, which helps reject other backgrounds which do not come from the target. Note that this chamber resides in vacuum, and was not installed for the 1994 run.

Fig. 2.3 and Fig. 2.4 show the elevation and plan view in the region of the two magnets.

2.3.4 Collimator

A collimator is placed inside M1 to limit the vertical acceptance to the detector fiducial region, and to shield the pole tips, coils, and vacuum chamber associated with M2. See Fig. 2.3 and Fig. 2.4. The collimator is made out of brass.
Figure 2.3: Magnets, collimator, and plug – elevation view. Note that the plug was not in place for the 1994 run.
Figure 2.4: Magnets and collimator – plan view.
2.4 Beam and Trigger Counters

2.4.1 Beam Čerenkov Counter (MITCH)

MITCH (MIT Čerenkov counter) is a 150 μm thick quartz plate counter used to count the beam. The Čerenkov plate is viewed by a top and bottom phototube (MITCH-A and MITCH-B). A relativistic heavy ion traversing the quartz plate emits light at the characteristic Čerenkov angle due to the Čerenkov effect. The amount of light emitted is proportional to the $Z^2$ of the incident particle. About 20,000 photoelectrons are produced when a relativistic gold ion passes through the 150 μm thick quartz plate. In addition, the signal from one Gold ion can be distinguished from that of two Gold ions, which allows us to reject the events in which two Gold ions pass through the target within our gate (double beam events).

For a heavy ion experiment, the Čerenkov counter has two great advantages over scintillation counters. The first is that quartz is far more radiation hard than solid scintillator. The second is that the physical Čerenkov process is faster than that of scintillator. Thus we obtain a clean signal which has good time resolution. In section 6.1 I derive a MITCH mean time resolution of 80 ps.

The main design effort of MITCH went into two areas. First, a good optical coupling between the quartz plate and the phototube is necessary to ensure that the light passes from the quartz plate to the phototube without reflecting. Second, the phototube and base must be able to handle a beam rate of $10^7$ Hz. The PMT anode currents must be maintained small to prevent the deterioration of the phototube, while maintaining time resolution. See [34] for details.

The counter is used to give us a start time (T0) for our analysis, and provides a strobe for the detectors.

2.4.2 Other Pretarget Counters

In addition to MITCH, there are two veto counters used to define a good beam. A quartz Čerenkov counter with a 1 cm hole is used to define the beam, and a large scintillation veto counter with a 2.75 cm hole is used to veto upstream interactions.
Figure 2.5: Target region geometry. There is a 5.5 cm diameter hole in the scintillation veto counter which is not shown.
The small counter is quartz because it is close to the beam, and scintillator would suffer radiation damage. The larger counter is further from the beam and shielded from the Au beam, so scintillator is acceptable. See Fig. 2.5. In chapter 3, details of the design of the pretarget system are presented.

2.4.3 Interaction Counter System (MULT)

MULT provides a measurement of the centrality of interactions in the target. It is made of four scintillation counters (MULTA, MULTB, MULTC, MULTD) which measure the rough centrality of the interactions, and can thus provide a centrality trigger. The centrality trigger requires an interaction in the target with sufficient multiplicity to indicate a central interaction. The number of interaction products indicate the centrality of an interaction because there is a large correlation between particle multiplicity and centrality in heavy ion collisions. For high-mass searches the MULT signal is fed into the "late energy" trigger, while for low-mass searches it serves as the trigger. Note that for the 1994 run the "late energy" trigger was not installed.

For the 1994 run MITCH was used to strobe the detectors.

The geometry of the interaction counter system is shown in Figs. 2.6 and 2.7.

MULT is made out of four 1 cm thick scintillation counters which are tipped at an angle of 8° with respect to the vertical and are located 13 cm downstream of the center of the target. The inner radius of the scintillator is 3.76 cm and the outer radius is 11.16 cm. The counter covers the angular range from 16.6° to 45.0° (\(\eta=\) pseudorapidity = 1.92 - 2.44).

The gold beam is in vacuum, and remains in vacuum until the end of our vacuum chamber 30 m downstream of the target. The vacuum chamber in the target region is made out of 1/8 inch thick aluminum. From our beam studies, we have determined that an appropriate inner diameter for the vacuum pipe is 1.5 inches.

A gold ion which passes through the target produces a cloud of delta rays. The delta rays can be attenuated with material. The shielding is designed so that a \(\delta\)-ray produced anywhere in the target must pass through at least 15 radiation lengths of material on its way to the interaction counter. The interaction products must also
Figure 2.6: Geometry of the interaction counter system.
pass through the shielding. It was found with Monte Carlo simulations that the attenuation due to the shielding does not impact the centrality selection. See chapter 4 for details of the Monte Carlo simulations which were used to design this counter.

2.5 Trigger for 1994 Run

A trigger is required to indicate when to record interesting events. The trigger logic for the 1994 run can be seen in Fig. 2.8.

The interaction counter (MULT) is used in the experiment to define three different interaction triggers:

1. Minbias (INT0). The minimus bias trigger requires a good beam and for the sum of pulses from the four interaction counters (MULT A-D) to have a threshold greater than 10 mV (this was the lowest threshold available on our discriminator units.) This selects roughly 98% of the total interaction cross-section.

2. Intermediate Multiplicity (INT1). The minimus bias trigger requires a good beam and that the sum of pulses from the four interaction counters (MULT
Figure 2.8: E864 trigger logic for the 1994 run.
A-D) to have a threshold greater than 200 mV. This selected approximately 20% of the interactions with highest multiplicities, corresponding to roughly the 20% most central triggers.

3. **Central (INT2).** The central trigger requires good beam and that the sum of pulses from the four interaction counters (MULT A-D) to have a threshold greater than 340 mV. This selected 10% of the interactions, and corresponds to roughly the 10% most central triggers (see Fig. 4.9)

A "good" beam particle requires:

1. Each of the split MITCH-A and MITCH-B to have a minimum threshold of 10 mV.

2. For MITCH-A and MITCH-B to be in time coincidence.

3. The sum of MITCH-A and MITCH-B lies between 60 mV (greater than gold) and 106 mV (less than the signal from two gold ions).

4. No hit in the scintillation hole veto.

5. No hit in the Čerenkov hole veto.

The Beam, Int0, Int1, and Int2 trigger then go to prescalers which allow us to select a desired set of ratios between the triggers. We accept most Int2 triggers, and prescale the Beam, Int0, and Int1 triggers to a desirable level. For the "+1.5T" running, the triggers were prescaled record approximately 70% Int2, 24% Int0, 4% Beam, 1% Int1, and 1% Pulser events. (The prescale values for the different triggers were set to: 0 for Int2, 25 for Int0, 1350 for Beam, and 150 for Int1.)

### 2.6 Detectors

#### 2.6.1 Hodoscopes (H1, H2, and H3)

The three scintillation counter hodoscopes give space, time, and charge points. They are segmented in the horizontal direction to give horizontal position resolution and
Table 2.2: Dimensions and location of the center of the scintillator hodoscopes.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Neutral Line Axis position (cm)</th>
<th>Horizontal Axis position (cm)</th>
<th>Vertical Axis Position (cm)</th>
<th>Vertical size (cm)</th>
<th>Horizontal Size (cm)</th>
<th>Rotation Angle (mr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
<td>1222.0</td>
<td>74.6</td>
<td>-47.9</td>
<td>63.6</td>
<td>227.59</td>
<td>111.7</td>
</tr>
<tr>
<td>H2</td>
<td>1629.4</td>
<td>105.9</td>
<td>-64.9</td>
<td>81.3</td>
<td>310.38</td>
<td>114.5</td>
</tr>
<tr>
<td>H2</td>
<td>2231.4</td>
<td>164.7</td>
<td>-81.5</td>
<td>106.4</td>
<td>475.12</td>
<td>116.8</td>
</tr>
</tbody>
</table>

acceptable occupancy. The vertical position is derived from the time difference between the phototubes which reside on the top and bottom of each hodoscope slat. The space points determine a rough slope and intercept of the downstream track. The time resolution of the hodoscopes is designed to at least resolve particle species which are up to at least half a unit above central rapidity. In fact, the resolution is good enough to resolve tracks with even higher rapidities. The pulse height spectrum, which is a measurement of the energy deposited of an ionizing particle traversing a scintillator slat, is proportional to the $Z^2$ of the ionizing particle. The three charge measurements allows one to reconstruct the charge of the track to a high accuracy. Thus, by themselves the hodoscopes give excellent tracks in space and time with redundant measurements to reduce the chances of constructing an incorrect track.

Each hodoscope plane consists of 206 scintillator slats, which all have both a top and bottom phototube. The signal from each tube is split: a small fraction of the signal goes into a high impedance discriminator which is located in the base and sent to a Time to Digital Converter (TDC) after being rediscriminated in the counting house, while the rest goes to an Analog to Digital Converter (ADC). The timing information (TDCs) from the top and bottom phototubes on a counter determine the space and time point for each hit, while the pulse height (ADCs) allow us to determine the charge of that hit.
Table 2.3: Hodoscope element details

<table>
<thead>
<tr>
<th>Detector</th>
<th>Number of slats</th>
<th>Width (cm)</th>
<th>Height (cm)</th>
<th>Thickness (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
<td>206</td>
<td>1.105</td>
<td>63.6</td>
<td>1.0</td>
</tr>
<tr>
<td>H2</td>
<td>206</td>
<td>1.506</td>
<td>81.3</td>
<td>1.0</td>
</tr>
<tr>
<td>H3</td>
<td>206</td>
<td>2.306</td>
<td>106.4</td>
<td>1.0</td>
</tr>
</tbody>
</table>

A novel feature of the hodoscope is the presence of a remotely adjustable Cockroft-Walton high voltage power supply in the base. Because the Cockroft-Walton base already requires low voltage, it is natural to split the signal and include a pulse discriminator in the base. This also has the advantage of improving the time resolution (the standard output pulse produced by the discriminator in the base is less sensitive to degradation due to dispersion in the cable between the phototube and the electronics racks). It also simplifies the cabling and control.

Figure 2.9 shows a section of the third hodoscope array. Tables 2.2 and 2.3 list the design location, dimensions and number of counters in each hodoscope. The hodoscopes are rotated around the $y$-axis, making approximately 115 mr angle with respect to the the initial beam direction ($z$-axis), so that they are perpendicular to the average track trajectory. This helps minimize the number of tracks which cross between two adjacent counters, which gives low pulse heights, and thus incorrect timing information.

Because we place the hodoscopes immediately under the vacuum chamber in to measure to low $p_t$ there is a 90° bend in the light guides. This leads to a loss of light, and thus a slightly worse time resolution. The light guides are 6" long, with H1 and H2 having a 5/8" diameter, and H3 having a 3/4" diameter. The light is sent to a Phillips XP2972 tube.

In the simulations for the proposal, time resolution of 156 ps, 173 ps, and 200 ps
Figure 2.9: A section of the third hodoscope array.
for H1, H2, and H3 respectively were assumed. In this analysis I derive resolution values of 130 ps, 118 ps, and 147 ps. See Sec. 7.3.4

The proposal took combined beam counter and hodoscope time resolutions of 164 ps, 180 ps, and 200 ps for H1, H2, and H3 respectively (this includes a 50 ps timing error due to MITCH). In comparison, the combined hodoscope and beam counter time resolutions at H1, H2, and H3 are 153 ps, 143 ps, and 167 ps respectively for the 1994 data (where the time resolution of mean of MITCH-A and MITCH-B was 80 ps).

The $z$ resolutions of the three hodoscopes are given by the slat width/$\sqrt{12}$. Thus the resolutions are 0.319 cm, 0.435 cm, and 0.666 cm for H1, H2, and H3 respectively.

The $y$ resolutions, which are derived from the time resolutions, because the $y$ position of a hodoscope slat is related to the time difference between the top and bottom phototube, and speed of light in the scintillator are 2.0 cm, 1.9 cm, and 2.4 cm for H1, H2, and H3 respectively.

### 2.6.2 Straw Tubes (S2 and S3)

The straw tube system provides precise position measurements for charged particles. This allows for a more accurate determination of the slope and intercept of the downstream track, which in turn leads to better rigidity reconstruction.

Straw tube chambers are proportional chambers constructed with a single anode wire centered in a metalized Mylar tube forming the grounded cathode.

Each straw tube chamber consists of three planes of doublet layers, $x$, $u$, $v$. The tubes of the $z$ layers are vertical, and thus measure the horizontal coordinate. The tubes of the $u$ and $v$ layers are inclined at ±20° to the vertical so that they provide a measurement of the vertical as well as the horizontal coordinate. Figure 2.10 shows a section of the contents of one straw tube array. The E864 straws are latched, or readout to indicate whether or not each straw is hit. They are not fed into a TDC.

Each straw is 4.0 mm in diameter. The resolution depends on the cluster size. Straw tube hits are associated together with neighboring hits into clusters. A particle traversing a straw plane will most likely fire one straw in each monolayer and, therefore, a cluster size of two is most likely. For a cluster size of one $\sigma_x = 0.4/\sqrt{12}$ cm =
Figure 2.10: Contents of one straw tube array.
Table 2.4: Dimensions and location of fiducial region of Straw Chambers from the 1994 survey. The horizontal and vertical axis positions are the position of the horizontal and vertical midpoints.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Neutral Line Axis position (cm)</th>
<th>Horizontal Axis position (cm)</th>
<th>Vertical Axis Position (cm)</th>
<th>Vertical size (cm)</th>
<th>Horizontal Size (cm)</th>
<th>Rotation Angle (mr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S2x</td>
<td>1058.05</td>
<td>62.21</td>
<td>-36.19</td>
<td>40.00</td>
<td>197.51</td>
<td>109.8</td>
</tr>
<tr>
<td>S2u</td>
<td>1083.98</td>
<td>62.84</td>
<td>-36.72</td>
<td>42.59</td>
<td>210.04</td>
<td>114.7</td>
</tr>
<tr>
<td>S2v</td>
<td>1023.35</td>
<td>56.03</td>
<td>-36.68</td>
<td>42.58</td>
<td>209.99</td>
<td>115.2</td>
</tr>
<tr>
<td>S3x</td>
<td>2017.16</td>
<td>137.68</td>
<td>-73.10</td>
<td>80.00</td>
<td>419.64</td>
<td>99.6</td>
</tr>
<tr>
<td>S3u</td>
<td>1951.98</td>
<td>-13.21</td>
<td>-73.82</td>
<td>85.34</td>
<td>112.40</td>
<td>100.9</td>
</tr>
<tr>
<td>S3v</td>
<td>1888.59</td>
<td>-27.56</td>
<td>-73.79</td>
<td>85.40</td>
<td>112.42</td>
<td>100.0</td>
</tr>
</tbody>
</table>

0.115 cm, for a cluster size of two $\sigma_x = 0.2/\sqrt{12} \text{ cm} = 0.0577 \text{ cm}$, and for a cluster size of three $\sigma_x = 0.6/\sqrt{12} \text{ cm} = 0.17 \text{ cm}$. The vertical resolution of a $u$ or $v$ layer is also a function of the straw cluster size, is given by $\sigma_v = \frac{\sigma_x}{\sin(20^\circ)}$ where $\sigma_x$ is the $x$ resolution of the same cluster size.

The straw tube chambers for the 1994 run can be seen in Figs. 2.1 and 2.2. In 1994, the S2 straw chamber was fully complete, while the S3 chamber had the full $x$ plane, but less than one third ($8/30$) of the $u$ and $v$ planes. The fiducial dimensions and number of tubes of each chamber is given in Tables 2.4 and 2.5.

The chambers operate with an Argon-CO$_2$-Ethane (90:9:1) gas mixture which permits operation with a gate width on the order of 40 ns. A gate width of 100 ns was used during the 1994 run.

S2 and S3 are rotated around the vertical by approximately the same amount as the hodoscopes so that they are perpendicular to the average charged particle track trajectory.
Table 2.5: Straw element details for the Fall 1994 run. It can be seen that less than one third of the S3 u and v chambers were present. The straws have a wall thickness of .002 inches, comprising of one layer of 0.001 in metalized Mylar, one layer of 0.0005 in metalized Mylar, and 0.0005 in of glue.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Number of straws</th>
<th>Width (mm)</th>
<th>Height (cm)</th>
<th>Straw Diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S2x</td>
<td>960</td>
<td>4.0</td>
<td>48.55</td>
<td>4.0</td>
</tr>
<tr>
<td>S2u</td>
<td>960</td>
<td>4.0</td>
<td>48.55</td>
<td>4.0</td>
</tr>
<tr>
<td>S2v</td>
<td>960</td>
<td>4.0</td>
<td>48.55</td>
<td>4.0</td>
</tr>
<tr>
<td>S3x</td>
<td>1920</td>
<td>4.0</td>
<td>90.20</td>
<td>4.0</td>
</tr>
<tr>
<td>S3u</td>
<td>512</td>
<td>4.0</td>
<td>90.20</td>
<td>4.0</td>
</tr>
<tr>
<td>S3v</td>
<td>512</td>
<td>4.0</td>
<td>90.20</td>
<td>4.0</td>
</tr>
</tbody>
</table>

2.6.3 Calorimeter

Independent of the tracking chambers, the calorimeter provides us with an additional mass measurement, giving us further rejection against background.

The E864 experiment uses a lead/scintillating fiber spaghetti calorimeter, which is based on the design of the SPACAL collaboration [36]. The spaghetti geometry consists of scintillating fibers, which run approximately parallel to the incoming particles, placed in lead. The spaghetti design calorimeter is nearly compensating (a calorimeter is compensating if it responds the same to electrons and hadrons) has excellent time resolution, good energy resolution, good spatial resolution, has a high rate capability, and is hermetic.

The full configuration of the calorimeter includes $58 \times 13$ towers, with each tower $10 \text{ cm} \times 10 \text{ cm} \times 1.17 \text{ m}$. See Figs. 2.11 and 2.12 for the details and a cross-sectional view of a single calorimeter tower. The 1994 version of the calorimeter included 180 towers mounted in an “L” shaped configuration as illustrated in shaded region of Fig. 2.13. The light from each tower is transmitted through a tapered lucite light guide and a Phillips XP2262B phototube, which is operated with Cockcroft Walton bases.
Figure 2.11: Details of an E864 calorimeter tower.

Figure 2.12: Cross-section of a single calorimeter tower using 1 mm diameter fibers and a lead-to-scintillator volume ratio of about 4:1. (Dimensions are in cm.)
Figure 2.13: Geometry of the E864 Calorimeter. The shaded region shows the portion of the calorimeter which was installed for the 1994 run.
Table 2.6: Dimension and Location of the nominal Calorimeter. The vertical and horizontal axis positions are measured to the midpoint of the calorimeter.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Neutral Line Axis position (cm)</th>
<th>Horizontal Axis position (cm)</th>
<th>Vertical Axis Position (cm)</th>
<th>Vertical size (cm)</th>
<th>Horizontal Size (cm)</th>
<th>Rotation Angle (mr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAL</td>
<td>1813.54</td>
<td>192.0</td>
<td>-98.73</td>
<td>110.0</td>
<td>560.0</td>
<td>57.6</td>
</tr>
</tbody>
</table>

similar to those are used on the hodoscopes. See [35] for details on the fabrication of the towers and test beam results from a 12 tower prototype.

From experimental data, the hadronic energy resolution of the calorimeter is between $\frac{\Delta E}{E} \approx 55\%/\sqrt{E}$ and $60\%/\sqrt{E}$, (where $E$ is in GeV) and the hadronic timing resolution is $\approx 450$ ps for the peak tower. The electromagnetic energy resolution of the calorimeter is $\frac{\Delta E}{E} \approx 20\%/\sqrt{E}$ from the test beam data, and the electromagnetic timing resolution is $\approx 235$ ps from experimental data. Approximately 95% of the energy of a shower is contained in a $3 \times 3$ cluster, where the center (or peak) tower has more energy than the surrounding 8 towers.

The calorimeter is rotated at an angle of approximately $3^\circ$ with respect to that of the average track. This is desirable in a spaghetti calorimeter geometry in order to prevent particles from directly going down a fiber. If the calorimeter were not rotated with respect to the incident particles, it would lead to poor electromagnetic resolution and possible high side tails in the energy distribution. A tilt angle of $4^\circ$ was found sufficient by the SPACAL collaboration [36].

2.7 Data Acquisition System

2.7.1 Introduction

The desire to be sensitive to rare states with a large acceptance open geometry spectrometer requires a high-rate data acquisition (DA) system. The E864 DA system
was designed to acquire 4000 events per AGS spill (where a typical event size was expected to be 6000 bytes and an AGS spill is on for one second every 4 seconds). Thus, to meet this goal we are required to digitize the 4000 events in one second, and record 24 MB/spill or 6 MB/sec. In addition, we would like to keep our dead time down to < 20%.

Fig. 2.14 shows the architecture of the E864 DA system. Below I describe the design of the DA system. For the 1994 run, the complete system was not up and running. The DA recorded approximately 1800 events per spill during the 1994 run. The event size was approximately 3500 bytes.

In order to design a DA system with these goals in mind, a parallel architecture was chosen. The data from four FASTBUS crates and four CAMAC crates are sent in parallel into six memory buffers which reside in VME. The event "fragments" are then recombined into complete events, and these events are then written to eight Exabyte tape drives in parallel. The E864 DA system was strongly influenced by the DA system of experiment E791 at Fermi National Accelerator Laboratory [38].

The E864 DA system was largely built with commercial products.

2.7.2 FASTBUS

The signals from the hodoscopes and calorimeter are sent into digitizers which reside in FASTBUS. In total, about 2000 ADC and 2000 TDC channels are sent into FASTBUS. Each FASTBUS digitizer can digitize 64 channels, and thus 34 ADC and 34 TDC cards are required. These are split up into four FASTBUS crates.

Fig. 2.15 a block diagram of the E864 FASTBUS system.

Since only a fraction of the E864 detectors are hit in each event, we save in the event size and readout time by suppressing channels which are not hit (zerosuppressing). We zero-suppress all of the TDCs, as well as the Hodoscope ADCs (the calorimeter ADCs must be read out because there is no clear separation between signal and pedestal in the calorimeter.).

The FASTBUS architecture is chosen because the only digitizers which meet our specifications reside in FASTBUS. In particular, we require fast digitization times with a relatively low cost per channel.
Figure 2.14: Block diagram of the E864 DA system.
FASTBUS Block Diagram

**Fastbus Data:**
- ~ 2000 ADC Channels (34 Cards)
- ~ 2000 TDC Channels (34 Cards)
- All TDC's 0 suppressed
- Hodoscope ADC's 0 suppressed

**Digitizers:**
- ADC's: *LeCroy 1881* 12 bit high res 15μs/card
- TDC's: *LeCroy 1872* 12 bit high res 12μs+2.5 μs/hit

**Controller:** *Fastbus Smart Crate Controller (FSCC)*
- Built by BIRa / Designed by Fermilab
- Motorola 68020 processor and programming memory
- RS485 differential TTL OPORT (32bit + strobe + wait)

---

Calorimeter Tower

$\times 754$

Hodoscope Slat

$\times 618$

---

Block Transfer

18 MB/sec

VME

---

Figure 2.15: FASTBUS Block Diagram.
The LeCroy 1881 and 1881M [39] were chosen for the ADC modules. The 1881 is a 12-bit high resolution ADC, while the 1881M is a 13-bit high resolution ADC. They both support zero-suppression, have a readout time 15 μs per card (64 channels), and have on-board buffering of digitized events (they can hold up to 64 events). In 1994 only 1881s were used. For future run the 1881s on the calorimeter are replaced with 1881Ms. The 1881s had the undesirable feature that occasionally (about one every thousand digitizations) it would return an incorrect value.

The LeCroy 1872A [39] was chosen for the TDC modules. The 1872A is a 12-bit high resolution TDC, which supports zero-suppression, has a readout time of 12 μs + 2.5 μs × (Number of hits), and supports on-board buffering of digitized events (they can hold up to 8 events).

The use on-board buffering of the digitizers allows us to reduce the dead time by decoupling the digitization time from the readout time. This was not used in the 1994 run.

The FASTBUS Smart Crate Controller (FSCC) [40] was chosen as the FASTBUS controller. It was designed by Fermilab and built by BiRa Systems Incorporated. The FSCC has a Motorola 68020 processor and programmable memory, which was programmed using the VxWorks 5.0.2b development system [41]. A key element to the FSCC is the 32-bit RS485 differential TTL Output Port (OPORT), which can be operated up to 10 MHz. We operated the OPORT at 6.67 MHz so that it would match the Matrix speed range (see the VME section). The FSCC allows us to get the data out of FASTBUS and into VME in a simple way as quickly as possible.

It is important to make an account of the time spent on various FASTBUS activities. Note that in order to meet our specification, we must be able to be ready for the next event within 50 μs and the total digitization and readout chain must take less that 250 μs.

**Digitization time**

First, the FASTBUS cards digitize one event's worth of data. The calorimeter TDCs will take the longest to digitize because the calorimeter has the highest occupancy and the TDCs take longer to digitize than the ADCs. For the full system, it was
expected that on the average a calorimeter TDC card will see 7 hits per interaction, which implies from Poisson statistics that one of the TDC cards will see 12 hits. Thus, we can be ready to readout the event after 42 \( \mu s \). When the on-board buffering of the digitizer is used, we are ready to take the next event immediately after we have digitized the previous event. Thus, we are ready for the next event within the required 50 \( \mu s \).

Readout time

- **Time to Broadcast Load Next Event** The ADCs and TDCs must be ready to accept the next event by incrementing the digitizers read pointer. The ADCs and TDCs accept broadcasts separately. Each broadcast takes 7.5 \( \mu s \), or a total of 15 \( \mu s \), to load the next event in all the digitizers.

- **Time to Address and De-address Each Card** In order to readout the data from the FASTBUS cards, each card must be addressed and de-addressed. This takes 1 \( \mu s \) per card. There are 10 ADCs and 10 TDCs in the crate with the most cards. Thus, this takes a total of 20 \( \mu s \) to address and de-address all the cards.

- **Time to Error Check** In order to ensure the integrity of the data, we check for FASTBUS errors several times during readout. It takes 2.0 \( \mu s \) each time we check for FASTBUS errors.

- **Time for the Block Transfer Between the Digitizer and the OPORT** The FASTBUS block transfer from the digitizers to the OPORT is measured to be 4.5 MHz (18 MB/sec). Thus, for a total event size of 6000 Bytes, we expect 1,500 Bytes per crate. Therefore, it takes 84 \( \mu s \) to transfer the data from the digitizer to the OPORT.

- **Time for the Transfer Between the OPORT and VME** The transfer rate from the OPORT to VME is 6.67 MHz (26.7 MB/sec). Thus, for a total event size of 6000 Bytes, it takes 56 \( \mu s \) to transfer the data from the OPORT to VME.
Table 2.7: FASTBUS Time to Digitize and Readout.

<table>
<thead>
<tr>
<th>FASTBUS Activity</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Digitization</td>
<td>42 $\mu$s</td>
</tr>
<tr>
<td>Broadcast LNE</td>
<td>15 $\mu$s</td>
</tr>
<tr>
<td>Address (1 $\mu$s/card)</td>
<td>20 $\mu$s</td>
</tr>
<tr>
<td>Error Checking (2.0 $\mu$s/check)</td>
<td>40 $\mu$s</td>
</tr>
<tr>
<td>Block Transfer (4.5 MHz)</td>
<td>83 $\mu$s</td>
</tr>
<tr>
<td>OPORT-VME Transfer (6.67 MHz)</td>
<td>56 $\mu$s</td>
</tr>
</tbody>
</table>

Total Time

Thus, the total digitization and readout time is approximately 250 $\mu$s. If this becomes the limiting factor in the DA speed, it is possible to reduce the error checking by approximately 30 $\mu$s.

See Table 2.7 for a summary of the time to perform various FASTBUS activities.

2.7.3 CAMAC

For the full system, the signals from approximately 9000 straws (from the 3 straw chambers) are sent into a CAMAC based system. The 1994 detector consisted of two straw chambers with a total of approximately 5800 straws. The LeCroy PCOS4 [42] system is used. Sixteen straws are sent into one chamber card which is mounted on the detector. The chamber card amplifies and shapes the signal, discriminates the signal (with a programmable threshold), delays the signal (by a programmable amount), and latches the signal (to send data only when a straw has been hit).

Fig. 2.16 shows a block diagram of the E864 CAMAC system.

The signals from 16 chamber cards are sent into a stream controller, which resides in CAMAC, through one cable. Four such cables can be attached to a single stream
CAMAC Block Diagram

Straw Tubes

Chamber Card

Pre Amp → Discr. → Latch

LeCroy PCOS IV System:
- Chamber Cards -- amplifier / discriminator / latch / delay
- System Controller
- Stream Controller

CAMAC Controller -- Smart Crate Controller (SCC)
- Built by BiRa / Designed by Fermilab
- Predecessor to FSCC -- same philosophy
- Same Output Bus as FSCC

Fast Cycle
3.3 MB/sec

Camac MUX

 SCC
controller. The data is read out by the Smart Crate Controller (SCC), the predecessor to the FSCC. The SCC supports a fast (600 ms) CAMAC cycle, and has a similar OPORT to the FSCC (it is only 16 bits wide and runs at 2 MHz). The SCC has a Motorola 6800 processor and the read out program is written in assembly language. Our trigger interrupt latency (the average time between receiving a trigger signal and beginning the read out process) was measured to be 6 μs.

The signals from the three straw chambers are sent into three different CAMAC crates. Along with the three straw CAMAC crates we have an additional CAMAC crate which contains event information. This information includes the trigger type and the phase of the 60 Hz AC power for each event.

Since the output speed of the RS485 OPORT on the SCC is well below the capability of the VME buffers, the data is sent from the four CAMAC crates into a CAMAC multiplexer (MUX), which combines the four input streams into one output data stream and packs pairs of 16 bit words into 32 bits. This output stream is then sent directly to VME. The multiplexer was designed and built at Yale University.

For the 1994 run the multiplexer was not built, so the two straw chambers that were present resided in one CAMAC crate, and was sent to VME directly. In addition, in 1994 the standard (1.2 μs) CAMAC cycle was used.

2.7.4 VME

Fig. 2.17 a block diagram of the E864 VME system.

The data from the FASTBUS and CAMAC input streams is sent into memory buffers which reside in VME. The memory buffers are a combination of two products: the DP-PCOMM communications module and the MD-CPU338 processor module [44]. The DP-PCOMM (a general purpose 32 bit RS485 input/output module which can operate up to 8.33 MHz, and supports VME-64 transfers) accepts the FASTBUS and CAMAC data and puts it into a 64 KB FIFO buffer. Events are then transferred into the memory of the MD-CPU338 (a general purpose CPU board with a Motorola 68030 processor and 8 MB of memory). The transfer from the FIFO to the memory buffer proceeds at approximately 20 MB/s.

Four event builders collect buffers of event fragments from the memory buffers
Figure 2.17: VME Block Diagram

Memory Buffers:  Matrix PCOMM+CPU338 -- 8MB memory + Motorola 68030 processor
Master, Event Builders:  General Micro Systems V49 -- Motorola 68040 processor
SCSI Controller:  Interphase SCSI4220 Cougar -- Dedicated I/O Controller

Eight Exabyte 8505 Dual Density Drives (.5MB/sec)
and rebuilds the fragments into full events. The event builders are GMS V49 boards [45] (a Motorola 68040 processor with 8 MB of memory). The event fragments are sent to the event builders via a block transfer at a rate of approximately 12 MB/sec.

The events are then sent from the event builders and into a SCSI controller via a VME-64 transfer at a rate of approximately 30 MB/sec. The SCSI controller is the Interphase V 4220 Cougar SCSI-II interface board [46], which supports VME-64 transfers. This controller provides a VME interface to two SCSI-II busses. Each of these busses is capable of driving 5 tape drives at full speed.

To meet the design goals, the data is written to eight Exabyte 8505 8mm dual density tape drives. These drives can write at a rate of 0.5 MB/sec. For 1994, four tape drives were written in parallel.

For details of the VME system see [37].

2.7.5 Summary of 1994 Run

The first (1994) experimental run of the E864 apparatus consisted of roughly four weeks of commissioning the detectors, followed by two weeks of physics running. During the physics running over 26.5 Million central triggers, or close to 100 GBytes of data, were taken at the “B=+1.5T” field setting. The results presented in this thesis are derived from the analysis of these triggers.
Chapter 3

The E864 Beam

3.1 Transport Beam Tune

The program Transport [49] was used to design the beam optics. A combination of old transport files and survey sheets were used to construct a transport file from the exit point of the AGS (F13) to a target in the E864 experimental area. The survey sheets are contained in Appendix I. Note that the distances on the survey sheets represent the distance from the center of the last bend in inches. The specifications of the magnets are determined from the magnet type of the survey sheet by using the map of magnets provided in Appendix II. Once the magnet type is known, more information, including the magnet’s effective length, can be found in the AGS Magnets book [51]. The field of the dipoles is determined from their bearing, which can be read off the survey sheets:

\[ B = 33.356 \frac{p}{\rho} \]
\[ = 33.356 \frac{p\theta}{L} \]

where the field of the dipole \( B \) is in kG, the beam momentum \( p \) is in GeV/c, the radius of curvature \( \rho \) is in meters, the bending angle \( \theta \) is in rad, and the effective length of the magnet \( L \) is in meters.

In addition to the experimental constraints outlined in Table 2.1, the beam was designed with several AGS layout considerations. Adequate space for shielding in
front of the EEBA Rectifier House transverse to the beam line was required, and adequate space for a beam dump upstream of roll-up door number 13 in the EEBA Rectifier House was required to preserve that door.

AQ5 and AQ6 were replaced with stronger quadrupoles and an additional bending magnet was needed in order to achieve a tune which meets the above constraints, The Transport beam tune is shown in Fig. 3.1. Note that the transport numbers do not take into account apertures or collimators.

Tables 3.1 and 3.2 include quadrupole and dipole information about the beam tune. In the transport tune (which does not take into account apertures or collimation) the horizontal divergence of the beam at the E864 target is 0.986 mr while the vertical divergence is 2.630 mr.

3.2 Angle Collimation

For the E864 experiment it is important that the vertical angular divergence be small (< 2 mr), and crucial the divergence have no tails. If the divergence is too big or if the distribution has large tails, beam particles will hit the vacuum chamber, which is at an angle of 4 mr to the beam. Thus, we would like to limit the angular divergence at the E864 target by collimating somewhere.

The trajectory of an arbitrary charged particle at any position in a system can be represented by a vector, and its passage through a system may be represented by the matrix equation

$$X' = RX$$

where $X$ is the initial coordinate vector, $X'$ is the final coordinate vector, and $R$ is the transfer matrix which describes the action of the optics on the particle coordinates. The coordinate vector's components are:

- $x$ the horizontal displacement from central trajectory
- $\theta$ the horizontal angle with respect to the central trajectory
- $y$ the vertical displacement from central trajectory
- $\phi$ the vertical angle with respect to the central trajectory
Figure 3.1: Horizontal and Vertical Beam Ellipse for the E864 Transport Tune.
Table 3.1: Quadropole information on the E864 transport beam line tune. Note that x-siz and y-siz are the half sizes of the beam envelopes.

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Max Field (kG/In)</th>
<th>Distance from F13 (m)</th>
<th>Field (kG/In)</th>
<th>x-siz (cm)</th>
<th>y-siz (cm)</th>
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<td>F13</td>
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<td></td>
<td>0.000</td>
<td></td>
<td>1.026</td>
<td>0.269</td>
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<td>CQ1</td>
<td>3Q36</td>
<td>10.0</td>
<td>4.731</td>
<td>5.91800</td>
<td>1.587</td>
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<td>CQ3</td>
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<td>3.727</td>
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<td></td>
<td>150.300</td>
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<td>0.782</td>
<td>0.345</td>
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Table 3.2: Dipole information on the E864 beam line tune.

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<th>Name</th>
<th>Type</th>
<th>Max Field (kG)</th>
<th>Distance from F13 (m)</th>
<th>Field (kG)</th>
<th>Bend (deg)</th>
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<td>E864 Tgt</td>
<td></td>
<td>150.300</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
path difference from central trajectory

fractional momentum deviation ($\frac{\Delta p}{p}$)

Thus, we can write out the explicit matrix equation for the progression of a charged particle through an optical configuration:

$$
\begin{pmatrix}
    x \\
    \theta \\
    y \\
    \phi \\
    l \\
    \delta
\end{pmatrix} =
\begin{pmatrix}
    R11 & R12 & R13 & R14 & R15 & R16 \\
    R21 & R22 & R23 & R24 & R25 & R26 \\
    R31 & R32 & R33 & R34 & R35 & R36 \\
    R41 & R42 & R43 & R44 & R45 & R46 \\
    R51 & R52 & R53 & R54 & R55 & R56 \\
    R61 & R62 & R63 & R64 & R65 & R66
\end{pmatrix}
\begin{pmatrix}
    x \\
    \theta \\
    y \\
    \phi \\
    l \\
    \delta
\end{pmatrix}
$$

In this case, we are interested in the vertical divergence which can be written out as follows:

$$
\phi = xR41 + \theta R42 + yR43 + \phi R44 + lR45 + \delta R46
$$

The large terms in bold dominate, as the other matrix elements are approximately zero. The dominant terms can be characterized as follows:

$yR43$ Term controlled by collimating $y$

$\phi R44$ need $R44 \approx 0$

Therefore, the most straightforward way to limit the angular divergence is to collimate at the location from which $R44$ to the E864 target is equal to zero. This point is located immediately after A3D7. The effect of this collimation can be seen in Fig. 3.2.

Even though a collimator after A3D7 would be separated from the E864 target by two quadrupoles, a dipole, and concrete, there is a concern that gold interactions in the collimator might lead to background at the E864 experiment. Thus, the program GEANT [52] was used to determine the background of a collimator located just after A3D7. Fig. 3.3 illustrates the layout. Fig. 3.4 shows the simulation of one gold interaction at this point. (Note that for this picture neutrinos were not included, and
Figure 3.2: The effect on the vertical beam ellipse by collimating after A3D7.
Figure 3.3: Layout of the GEANT background study for interactions just after A3D7. Note that the scale is anamorphic.
Figure 3.4: GEANT simulation of one gold interaction in a collimator just after A3D7. Refer to Fig. 3.3 for the layout. Note that the scale is anamorphic.
Table 3.3: Transport matrix from A1C1 to A1C2

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<th>x</th>
<th>θ</th>
<th>y</th>
<th>φ</th>
<th>l</th>
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</tr>
</thead>
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<td>-0.61864</td>
<td>-0.05639</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>-0.72062</td>
</tr>
<tr>
<td>y</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>4.04827</td>
<td>0.00000</td>
<td>0.00000</td>
</tr>
<tr>
<td>φ</td>
<td>0.00000</td>
<td>0.00000</td>
<td>-0.24702</td>
<td>1.30840</td>
<td>0.00000</td>
<td>0.00000</td>
</tr>
<tr>
<td>l</td>
<td>0.08136</td>
<td>0.12390</td>
<td>0.00000</td>
<td>0.00000</td>
<td>1.00000</td>
<td>-0.00406</td>
</tr>
<tr>
<td>δ</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>1.00000</td>
</tr>
</tbody>
</table>

Table 3.4: Transport matrix from A1C1 to the E864 target

<table>
<thead>
<tr>
<th></th>
<th>x</th>
<th>θ</th>
<th>y</th>
<th>φ</th>
<th>l</th>
<th>δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>-0.13927</td>
<td>-2.90470</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.18394</td>
</tr>
<tr>
<td>θ</td>
<td>0.18390</td>
<td>-3.34466</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>1.40812</td>
</tr>
<tr>
<td>y</td>
<td>0.00000</td>
<td>0.00000</td>
<td>-0.12280</td>
<td>0.53897</td>
<td>0.00000</td>
<td>0.00000</td>
</tr>
<tr>
<td>φ</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.42558</td>
<td>-10.01085</td>
<td>0.00000</td>
<td>0.00000</td>
</tr>
<tr>
<td>l</td>
<td>0.02299</td>
<td>0.34750</td>
<td>0.00000</td>
<td>0.00000</td>
<td>1.00000</td>
<td>-0.30289</td>
</tr>
<tr>
<td>δ</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>1.00000</td>
</tr>
</tbody>
</table>

a 0.1 MeV energy cut was imposed.) Fig. 3.4 indicates that for each interaction in the collimator there are background particles in the vicinity of the E864 experimental area. These particles can lead to a background problem in the E864 experiment.

An alternative method to limit the vertical angular divergence at E864 is to use the two existing collimators (A1C1 and A1C2) together. From Tables 3.3 and 3.4:

\[ y_{A1C2} = 4.05 \phi_{A1C1} \]
\[ \phi_{E864} = 0.43y_{A1C1} - 10.01\phi_{A1C1} \]

from which

\[ \phi_{E864} = 0.43y_{A1C1} - \frac{10.01}{4.05} y_{A1C2} \]

Therefore, the angle at E864 can be controlled by collimating both A1C1 and A1C2. The effect on the beam ellipse at the E864 target by collimating A1C1 and A1C2 can
Figure 3.5: The effect on the beam ellipse by collimating both A1C1 (±1 cm) and A1C2 (±.25 cm)

be seen in Fig. 3.5. From Fig. 3.5 we can see that we get the added bonus of limiting the size of the beam as well as the divergence.

Again, we must check if interactions in A1C2 leads to backgrounds at E864. Fig. 3.6 shows the layout of this simulation, and Fig. 3.7 shows the simulation of one gold interaction at A1C2. (Note that for this picture neutrinos were not included, and a 0.1 MeV energy cut was imposed.) In 54 events, there was no background. Thus, both A1C1 and A1C2 are used to limit the angular divergence at the E864 target.

3.3 Ramping

3.3.1 Introduction

During extraction the beam energy changes by about 1% (Δp / p ≈ 1%). This change of momentum results in a variation of the transverse spot location and angle during the spill. There are two methods to correct for this change: the beam line can be
Figure 3.6: Layout of the GEANT background study for interactions in A1C2. Note that the scale is anamorphic.
Figure 3.7: GEANT simulation of one-gold interaction at A1C2. Refer to Fig. 3.6 for the layout. Note that the scale is anamorphic.
designed so that the spot location and angle is insensitive to a momentum change (the transport array elements R16 and R26 equal zero), or the magnet currents can be adjusted during the spill (or ramped), so as to correct the angle and position variations. If all the magnets are ramped, then tuning the magnet currents so that \( \frac{\Delta B}{B} = \frac{\Delta p}{p} \) leads to a fixed beam location and angle. However, not all the magnets are ramped, and therefore, those magnets that are ramped need to bend harder to keep the spot fixed. This leads to an imperfect correction of the transverse angle, and thus the angle will vary during the spill.

The A line at the AGS is not designed so that R16 from the extraction point (F13) to the A-station is zero, and thus the magnets are ramped: F13 is ramped to keep a fixed spot in front of CD1; CD1 is ramped to keep a fixed spot in front of AD2; AD2 and AD3 are ramped to keep a fixed spot at AD5; and AD5, AD6, AD7, and AD8 are ramped to keep a fixed spot at the A-target.

The E864 beam tune is designed so that R16 from the A-station to the E864 target is small, and the R16 from AGS extraction (at F13) to the A-station is made zero by ramping certain magnets upstream of the A-station. This leads to a fixed spot and changing angle at the A-station. In the E864 beam tune design, the matrix element that translates angle at the A-station to position at the E864 target (R12) is \(-2.9 \text{ cm/mr}\). Therefore, if the transverse angle at the A-station varies by 1 mr, the spot location at E864 will walk by 2.9 cm.

The spot at E864 can be made fixed by putting a SERVO SWIC near the E864 target, which corrects a SERVO magnet upstream.

In the following sections contain estimates how much the beam walks the E864 target in the absence of ramping or SERVOing downstream of the A-station, and give the requirements for the location and power for a SERVO magnet.

### 3.3.2 Effects of ramping

**Method to determine the angular divergence stability at the A-station**

In this section an example of a subset of magnets is used to show the method used to calculate the angular stability at the A-station.
Fig. 3.8 illustrates the situation. Note the flags are scintillation which allow the AGS operators to determine the location of the gold beam. In this case, we are concerned about the ramping of the magnets between B and C. We assume that the spot position is held constant at C \((R16(D \rightarrow C) = 0)\) by ramping magnets between \(D\) and \(C\). This section contains an outline of how to estimate \(\theta_{A\text{-station}}\left(\frac{\Delta p}{p}\right)\) due to the set of magnets between \(D\) and \(C\).

The first step is to determine at what fields to run the ramped magnets. We assume that

\[
\frac{\Delta B_i}{B_i} = \frac{\Delta \theta_i}{\theta_i} = (0.01)k \left(\frac{\Delta p}{p}\right)\%
\]

If all the magnets are ramped, the constant \(k = -1\). However, not all the magnets are ramped, and we must determine \(k\). The displacement of the changing magnetic fields in the ramped magnets \((\Delta \theta_i(1\%))\) plus the displacement if the magnets are not ramped \((R16(C \rightarrow B))\) is equal to zero:

\[
\sum_{i \text{ramped}} R_{12}(z_i \rightarrow B)\Delta \theta_i(1\%) + R16(C \rightarrow B) = 0
\]

This can be solved for \(k\):

\[
k = \frac{-R16(C \rightarrow B)}{(0.01) \sum_i R_{12}(i \rightarrow B)\theta_0(i)}
\]

Thus, if we set the ramped magnets as determined by \(k\), the position at \(B\) is held fixed, and we can calculate how much the angular divergence at the A-station changes
due to this set of magnets:

\[
\theta_{A\text{-station}} \left( \frac{\Delta p}{p} \right) = \sum_{n=\text{all mag}} R_{22}(n \rightarrow A)\theta_{0}(n)(.01) \left( \frac{\Delta p}{p} \right)_{\%} \\
+ \sum_{i=\text{ramped}} R_{22}(i \rightarrow A)\theta_{0}(i)(.01)k \left( \frac{\Delta p}{p} \right)_{\%}
\]

We are now ready to apply this method to E864.

Estimation of the angle variation at the A-station

The program Transport was used to calculate the matrix elements required to calculate \( k \) and \( \theta \). For the E864 situation, we have to sum the contribution of three sets of ramped magnets. A summary of these results is presented in Table 3.5.

Applying the formulas that were derived in Section 5.2.1, We arrive at

\[
\theta_{A\text{-station}} (1\%) = 0.16 \text{ mr}
\]

which leads to a walk of

\[
(0.16 \text{ mr}) \left( 2.9 \frac{\text{ cm}}{\text{ mr}} \right) = 0.45 \text{ cm}
\]

at E864.

In the 1994 run we observed walking that is consistent with the above prediction in the absence of ramping or SERVOing.

### 3.3.3 Ramping and SERVOing in the A3 Beam Line

A combination of ramping magnets and one SERVO magnet is used to correct for walking that was presented in the last section.

The SERVO SWIC is placed in a location where a fixed spot at the SWIC leads to a fixed spot at the E864 target (R16(SWIC \( \rightarrow \) tgt) = 0). It is located in an air break just upstream of the target. See Fig. 4.1.
Table 3.5: Ramping. $\theta_0$ is the unramped bend angle; R12 is taken from the exit of the magnet to the next set of ramped magnets; R22 is taken from the exit of the magnet to A1C2; R16 is taken from the entrance of the magnet to the front of the next set of ramped magnets. Ramped magnets are indicated by a *; and sets of ramped magnets are separated by blank lines.

<table>
<thead>
<tr>
<th>Name</th>
<th>$\theta_0$ (rad)</th>
<th>R12 (cm/mr)</th>
<th>R22 (mr/mr)</th>
<th>R16 (cm/%)</th>
<th>R12+$\theta_0$</th>
<th>R22+$\theta_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD1*</td>
<td>-12.005596</td>
<td>4.13084</td>
<td>-0.59451</td>
<td>-0.48427</td>
<td>-49.59356</td>
<td>7.13745</td>
</tr>
<tr>
<td>AB1</td>
<td>-0.375228</td>
<td>1.70259</td>
<td>-0.37204</td>
<td></td>
<td>-0.63737</td>
<td>0.13927</td>
</tr>
<tr>
<td>DB3</td>
<td>-0.375228</td>
<td>1.35969</td>
<td>-0.30761</td>
<td></td>
<td>0.50901</td>
<td>-0.11516</td>
</tr>
<tr>
<td>BB3</td>
<td>0.133221</td>
<td>1.01679</td>
<td>-0.24318</td>
<td></td>
<td>-0.13546</td>
<td>0.32397</td>
</tr>
<tr>
<td>AD21*</td>
<td>-17.373269</td>
<td>2.74992</td>
<td>-0.02992</td>
<td>-1.79221</td>
<td>-47.72231</td>
<td>0.51923</td>
</tr>
<tr>
<td>AD22*</td>
<td>-17.354071</td>
<td>2.60276</td>
<td>-0.00718</td>
<td></td>
<td>-45.16848</td>
<td>0.12460</td>
</tr>
<tr>
<td>AD31*</td>
<td>-16.600176</td>
<td>2.38503</td>
<td>0.02662</td>
<td></td>
<td>-39.59192</td>
<td>-0.44190</td>
</tr>
<tr>
<td>AD32*</td>
<td>-16.600176</td>
<td>1.52020</td>
<td>0.04935</td>
<td></td>
<td>-25.23559</td>
<td>-0.81922</td>
</tr>
<tr>
<td>AD4</td>
<td>-22.316216</td>
<td>0.09143</td>
<td>0.45426</td>
<td></td>
<td>-2.04082</td>
<td>-10.13736</td>
</tr>
<tr>
<td>AD5*</td>
<td>-22.319829</td>
<td>2.38198</td>
<td>0.55318</td>
<td>-2.35769</td>
<td>-53.16539</td>
<td>-12.34688</td>
</tr>
<tr>
<td>AD6*</td>
<td>-22.319829</td>
<td>2.22435</td>
<td>0.65093</td>
<td></td>
<td>-49.64711</td>
<td>-14.52864</td>
</tr>
<tr>
<td>AD7*</td>
<td>-22.319829</td>
<td>2.06667</td>
<td>0.74866</td>
<td></td>
<td>-46.12772</td>
<td>-16.70996</td>
</tr>
<tr>
<td>AD8*</td>
<td>-22.319829</td>
<td>1.88167</td>
<td>0.86327</td>
<td></td>
<td>-41.99175</td>
<td>-19.26492</td>
</tr>
<tr>
<td>AD9</td>
<td>-22.321644</td>
<td>1.72202</td>
<td>0.96213</td>
<td></td>
<td>-38.43843</td>
<td>-21.47632</td>
</tr>
</tbody>
</table>
The SERVO magnet is located in between A3Q5 and A3Q6. The strength required of the magnet can be calculated from Transport:

\[
\theta = \frac{1}{R_{12}(\text{mag \to \text{E864}})} \quad x = 0.68 \, \text{mr / cm motion}
\]

\[
\int Bdl = (3.33) \left( 28.5 \frac{\text{GeV}}{c} \right) \theta \quad [\text{Tm}]
\]

\[
= 0.06 \, \text{Tm / cm motion}
\]

The SERVO magnet is a 6.75D24 gaped down to 4.125 inches. This magnet can produce a central field of 1.75 kG which corresponds to 1.75 cm of motion at the E864 target.

Thus, in principal the SERVO system alone stabilizes the beam.

We must now consider the fact that we collimate at A1C2. The R12 between A1C1 and A1C2 is 1.6 cm/mr. Thus, if we collimate strongly at A1C2, we will get a bad beam spill because the beam will sweep past the collimator. The solution to this is to ramp A1D3 and A1D4. The SERVO magnet then does the fine tune adjustment to stabilize the beam.

This system works extremely well, and leads to a nice stable beam spot at the E864 target.
Chapter 4

Pretarget and Target Region

4.1 Pretarget Detector System

The E864 pretarget detectors define good beam particles, which are a requirement for our trigger. The geometry can be seen in Fig. 4.1.

The gold beam is transported to the E864 area in an 7.62 cm outer diameter vacuum pipe up until 254 cm before the target (z=−254 cm). At that point the beam pipe becomes a 6.35 cm outer diameter vacuum pipe, and iron shielding is placed outside the beam pipe. This shielding protects the scintillation hole veto counter and other pretarget phototubes from the gold beam. A vacuum window is located at z=−177.8 cm so that the E864 pretarget detectors can be placed in air.

The pretarget detectors consist of FIDO, a universal SWIC, a Čerenkov hole veto counter, MITCH, and a scintillation hole veto counter. FIDO is a quartz fiber hodoscope that will count the beam (this detector was not installed for the 1994 run). The universal SWIC (Segmented Wire Ion Chamber) contains a SERVO SWIC, beam position monitor, and intensity monitor. The quartz Čerenkov veto counter is used to define the beam and detect upstream interactions. MITCH is a 150 μm thick quartz plate Čerenkov counter used to count the beam. The scintillation veto counter covers the region outside the quartz hole veto counter, and is located so that it can detect interactions in and downstream of MITCH.
Figure 4.1: Pretarget Geometry.
Table 4.1: Summary of material in the Beam.

<table>
<thead>
<tr>
<th>Name</th>
<th>Location (cm)</th>
<th>Thickness</th>
<th>Material</th>
<th>$L_R$</th>
<th>% $L_R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Window</td>
<td>x=–177.8</td>
<td>0.0762 mm</td>
<td>Aluminum</td>
<td>4.72 cm</td>
<td>0.16%</td>
</tr>
<tr>
<td>Air</td>
<td>x=–177.8</td>
<td>88.9 cm</td>
<td>Air</td>
<td>6091 cm</td>
<td>1.46%</td>
</tr>
<tr>
<td></td>
<td>→ –88.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FIDO</td>
<td>x=–158.75</td>
<td>150 μm</td>
<td>Quartz</td>
<td>3.84 cm</td>
<td>0.39%</td>
</tr>
<tr>
<td>Universal SWIC</td>
<td>x=–127.0</td>
<td>0.0889 cm</td>
<td>Kevlar</td>
<td>3.34 cm</td>
<td>1.30%</td>
</tr>
<tr>
<td>2 Windows</td>
<td></td>
<td></td>
<td>Aluminum</td>
<td>4.72 cm</td>
<td></td>
</tr>
<tr>
<td>11 Foils</td>
<td></td>
<td>0.0254 cm</td>
<td>Alumunium</td>
<td>4.72 cm</td>
<td></td>
</tr>
<tr>
<td>3 planes wire</td>
<td></td>
<td>20 μm</td>
<td>Tungsten</td>
<td>2.64 cm</td>
<td></td>
</tr>
<tr>
<td>Gas</td>
<td></td>
<td>15.24 cm</td>
<td>Argon</td>
<td>9640 cm</td>
<td></td>
</tr>
<tr>
<td>MITCH</td>
<td>x=–97.79</td>
<td>150 μm</td>
<td>Quartz</td>
<td>3.84 cm</td>
<td>0.39%</td>
</tr>
<tr>
<td>Window</td>
<td>x=–86.0</td>
<td>0.0762 mm</td>
<td>Aluminum</td>
<td>4.72 cm</td>
<td>0.16%</td>
</tr>
</tbody>
</table>

The material in the beam in the immediate area upstream of the target is summarized in Table 4.1.

4.2 Scintillation Hole Veto Counter

The purpose of the scintillation hole veto counter is to detect upstream interactions in the windows, air, FIDO, universal SWIC and MITCH. In particular, this counter is downstream of MITCH and the last vacuum window, and is the only counter which can detect interactions in MITCH or the downstream window. In addition, it extends further out in radius than the Čerenkov veto counter.

In addition to upstream interactions, the scintillation veto counter is subject to counts from δ-rays produced by the gold beam and by albedo from interactions the
Table 4.2: Summary of shielding and scintillation veto counter.

<table>
<thead>
<tr>
<th>Name</th>
<th>Distance from Target (cm)</th>
<th>Thickness along Beam</th>
<th>Inner Radius</th>
<th>Horizontal Full Size</th>
<th>Vertical Full Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead Shield</td>
<td>-69.8898</td>
<td>30.900 cm</td>
<td>2.54 cm</td>
<td>18.00 cm</td>
<td>21 cm</td>
</tr>
<tr>
<td>Lead Shield</td>
<td>-46.5629</td>
<td>13.876 cm</td>
<td>2.54 cm</td>
<td>14.02 cm</td>
<td>21 cm</td>
</tr>
<tr>
<td>Veto Counter</td>
<td>-53.9699</td>
<td>0.6350 cm</td>
<td>2.75 cm</td>
<td>17.00 cm</td>
<td>17 cm</td>
</tr>
</tbody>
</table>

the E864 target. Thus, a shield upstream of the scintillation counter is needed to protect it from δ-rays, and a shield downstream of the counter is needed to protect it from albedo from interactions in the target.

The veto counter is square, with a circular hole cut out so that it is located outside of the aluminum beam pipe and inside the acceptance of the Čerenkov veto counter. The upstream and downstream lead shields are rectangular with a circular hole cut. The dimensions of the shields and scintillation counter is given in Table 4.2.

A Monte Carlo simulation was carried out to design the shielding required upstream and downstream of the scintillation hole veto counter and to study the efficiency that this counter has in vetoing interactions in MITCH.

4.2.1 Albedo from Target

Interactions in the target have the potential of producing backsplash which counts in the scintillation hole veto counter. In order to bring these occurrences down to an acceptable level, shielding is required between the target and veto counter.

E864 has a view port which allows us to put a camera on and view a scintillator flag at the target. This allows us to see the beam at our target. This port puts a space constraint on the shielding. We put the most shielding possible, while taking this constraint into account. The Monte Carlo studies indicated that a heavy shielding material is necessary. We chose lead.
In GEANT [52], with all the physical processes turned on, 1000 Minbias Au+Pb interactions were generated and information about all particles entering the veto counter was recorded. (Minbias events refer to events which include all impact parameters which have elastic interactions.) The Monte Carlo simulations indicate shielding design presented in Table 4.2 is adequate. In 1000 Minbias events 2 charged particles and 149 neutral particles enter the scintillator.

The scintillation veto counter cannot extend past 9 cm because of the space constraints. The counter extends far enough to shadow MULT. This allows us to veto upstream interactions which deposit energy in MULT.

4.2.2 Delta Rays from the Pretarget Counters

The gold beam passes through the material summarized in Table 4.1, producing δ-rays. Some of these δ-rays can hit the scintillation veto counter. In order to get this rate to an acceptable level, shielding is needed in front of the counter. In this section I report on the results of the monte carlo program that was used to design shielding to protect the scintillation veto counter from these δ-rays.

In GEANT, with all the physical processes turned on, 1000 gold nuclei were generated. These nuclei pass through the material in the beam line (see Table 4.1 and Fig 4.1) creating δ-rays. Fig. 4.2 shows the origin vertex location along the beam line for charged particles which hit the veto counter.

Approximately 8% of beam particles will deposit at least one charged particle in the scintillator. Thus, the threshold of this counter will have to be set greater than 1 minimum ionizing particle.

4.2.3 Efficiency

The efficiency of the scintillation veto counter to detect interactions in MITCH was calculated by Monte Carlo.

1000 Minbias Au+Quartz interactions in MITCH were generated. In Fig. 4.3 the efficiency is plotted as a function of threshold of charged particles. Thus, if we put a threshold of 2 charged particles, 72% of the time the counter will detect interactions
Figure 4.2: $\delta$-rays produced by the traversal of 1000 gold nuclei through the pretarget in-beam material. The creation point along the beam axis for charged particles which hit the veto counter is plotted.
Figure 4.3: 1000 Minbias interactions in MITCH. Efficiency, as a function of charged particle threshold, of the scintillation veto counter to detect interactions in MITCH.
4.2.4 Conclusions

This study demonstrates that a veto counter as described is useful in vetoing interactions in and downstream of MITCH.

The albedo from interactions in the target is shielded against adequately, however δ-rays produced in MITCH somewhat compromise the efficiency of detecting interactions in MITCH.

4.3 Interaction Counter (MULT)

A Monte Carlo simulation was carried out to design the interaction counter system. These studies aided in designing the geometry of the system as well as predicting the performance of the detector.

4.3.1 Delta Rays from the Target

In this section I report on how the δ-ray shielding for the MULT counter was designed.

Events in which a gold ion which passes entirely through the target without interacting were simulated with GEANT [52] in order to determine the counting rate at MULT due to δ-rays. The computer simulation showed that with no shielding ≈ 140 counts are recorded and ≈ 160 MeV is deposited into the scintillator array per beam traversal (See Fig. 4.4.) The δ-rays are of relatively low energy (see Fig. 4.4), and thus can be attenuated with material. The high-Z material has the disadvantage that δ-rays bremsstrahlung more in high-Z material than low-Z material. Thus, if we had the same number of radiation lengths of a low-Z material, more energy loss would go into ionization. However, we have severe space constraints and therefore must use a high-Z material. We choose 90% tungsten alloy for our shielding.

A second beam particle interacting after a triggered event has satisfied the centrality requirement can fake a strangelet signal. Thus, it is desirable for the interaction
Figure 4.4: The geometry includes ONLY the target and scintillator. (a) Total Energy deposited in GeV into the scintillation array for 1000 gold nuclei passing through a 10% lead target without interacting. Note that there is one entry per counter per event, or four per event. Thus, it can be thought of equivalently as 4000 events in a system where only 1 out of the four scintillation sections were present. (b) Kinetic energy distribution for the \( \delta \)-rays which hit the scintillation array.
counter to be sensitive enough to detect and veto second interactions within our time window. Very peripheral interactions may only deposit a few particles into the interaction array, and thus it is desirable to be sensitive to a single minimum ionizing particle (MIP). One MIP deposits approximately 2 MeV when passing through 1 cm of scintillator. Thus, the shielding must be designed to attenuate the δ-rays so that non-interacting beam particles which simply traverse the target rarely fake peripheral interactions. This will insure that good events are not often vetoed by these δ-ray events. The Monte Carlo was used to estimate how often the δ-rays from a gold ion traversing the target deposit the same amount of energy as one MIP.

The geometry, which is presented in Figs. 2.6 and 2.7 and includes the vacuum pipe, and shielding, provides an acceptable solution. See Fig. 4.5 for the energy deposited into the interaction counter. Thus, 14 times in 1000 events δ-rays fake a MIP. If we take a gate of 30 ns and a beam rate of $10^7$ gold ions per second with a flat spill structure, we can estimate the percent of δ-ray events which fake second interactions:

$$(30 \times 10^{-9} \text{ sec}) \left(10^7 \frac{\text{events}}{\text{sec}}\right) \left(\frac{14}{1000}\right) = 0.42\%$$

Note that if this is possible, it is much better than vetoing all second beams, because with a beam rate of $10^7$ and a gate of 30 ns and assuming a flat spill structure, 30% of all events contain a second beam.

Thus, the shielding as designed reduces the rate and energy deposited from the events in which δ-rays are produced to an acceptable level.

### 4.3.2 Minbias Interactions

In this section I report on how well the MULT counter discriminates between central and peripheral interactions with and without the δ-ray shielding.

First, the discrimination between central and peripheral events was studied with vacuum between the target and scintillator. An event is simulated with GEANT by sending an 11.71 GeV/c per nucleon gold ion through a 10% lead target. This ion produces δ-rays until it interacts at a random depth in the lead target. This collision
Figure 4.5: Total Energy deposited in GeV into the scintillation array for 1000 gold nuclei passing through the 10% lead target without interacting. Note that there is one entry per counter per event, or four per event. Thus, it can be thought of equivalently as 4000 events in a system where only 1 out of the four scintillation sections were present. The geometry includes the target, vacuum pipe, shielding, and scintillator.
is simulated by the HIJET [53] event generator. The interaction products and \( \delta \) -rays proceed through the target and into the vacuum chamber, shielding, or vacuum region. Particles then deposit energy into the scintillator. All of GEANT's physics processes were turned on for the simulation.

This study indicated that even a one counter trigger gives good central/peripheral discrimination. Under experimental conditions this means that a four counter system is be adequate. The segmentation is useful for rejecting fake triggers due to upstream interactions, etc. Studies with more counters were also carried out, however no simple trigger algorithm gave better discrimination for events coming from the target than the one counter system.

Fig. 4.6 is a scatter plot of integrated \( dE/dx \) per event versus impact parameter for 1000 events. I will refer to the integrated \( dE/dx \) per event as simply \( E_{\text{dep}} \). We wish to make a \( E_{\text{dep}} \) cut so that we accept approximately 10% of the events. Because of the correlation between \( E_{\text{dep}} \) and impact parameter, these events will be quite central. Fig. 4.7 is a plot of the distribution of impact parameters that pass a 0.739 GeV \( E_{\text{dep}} \) cut. This demonstrates that approximately 10% of the events are selected, and those events which are selected are the most central. Fig. 4.7 is a plot of the distribution of impact parameters which pass the 0.739 GeV \( E_{\text{dep}} \) cut divided by the the distribution of impact parameters for all events. This plot gives the probability that an event with a particular impact parameter passes the \( E_{\text{dep}} \) cut.

We next studied how the addition of shielding affects the discrimination between central and peripheral events. Fig. 4.8 is a scatter plot of \( E_{\text{dep}} \) per event versus impact parameter for 1000 events. To select the 10% most central events, we impose a \( E_{\text{dep}} \) centrality cut. Fig. 4.9 shows the distribution of impact parameters that pass this cut and the probability that an event with a particular impact parameter passes the \( E_{\text{dep}} \) cut. In addition to a 10% cut, a 5% and 1% cut are also shown. Fig. 4.9 demonstrates that the multiplicity counter can be used to roughly select the centrality of an event. For example, if we make a cut on events with the 10% highest pulse heights, we are selecting events with the 10% smallest impact parameters 88% of the time. Even higher pulse height cuts result in higher centrality events, although with very high cuts the acceptance for these high centrality events also goes down.
Figure 4.6: Correlation between $E_{\text{dep}}$ and impact parameter for 1000 Au+Pb events. The geometry includes ONLY the target and scintillator.
1000 Au+Pb Minbias Events —— No Shielding

Figure 4.7: 1000 Au+Pb minbias events. The geometry includes ONLY the target and scintillator. (a) Distribution of impact parameters which pass a $E_{\text{dep}} > 0.739$ GeV cut. (b) Trigger probability for a particular impact parameter event to pass the $E_{\text{dep}} > 0.739$ GeV cut.
Figure 4.8: Correlation between $E_{\text{dep}}$ and impact parameter for 1000 Au+Pb events. Full geometry.
17,500 Au+Pb Minbias Events — Full Geometry

Figure 4.9: 17,500 Au+Pb minbias events. Full geometry. Monte Carlo study of the centrality selection of the multiplicity counter. The three different curves represent different cuts on the energy deposited in the multiplicity counter. The solid line represents a cut on the events with the 10% most energy deposited, the dashed line represents the 5% most energy deposited, and the dotted line represents the 1% most energy deposited. (a) Distribution of impact parameters (in fm) which pass a 10%, 5%, and 1% cut on the energy deposited in the four scintillator counters in the multiplicity counter. (b) Trigger probability for a particular impact parameter event to pass a 10%, 5%, and 1% energy deposit cut. For the 10% cut $E_{\text{dep}} > 0.35$ GeV.
Thus, the addition of the shielding does not affect the central/peripheral discrimination.

4.3.3 Light Collection

It is desirable for the interaction counter to be fast enough to provide a strobe for the E864 detectors, and to have a fast fall time so that we can veto second interactions as soon as possible after the first interaction. (Note that for the 1994 run the MITCH counter strobed the E864 detectors.) Thus, the sides of the scintillator and light guide are blackened. This decreases the fall time by only accepting photons with a direct path to the phototube. It leads to approximately a factor of two less light, and therefore it was important to estimate the amount of light we collect.

The light guide is designed to collect all the light that is directed toward the 2 inch phototube. This geometry can be seen in Figs. 2.6 and 2.7. Only a fraction of the light from a particle which traverses the scintillator can make a direct path to the phototube. This is referred to as the fractional solid angle. In the Monte Carlo program the geometrical fractional solid angle is recorded in several places as a particle traverses the scintillator. The distribution of fractional solid angles can be seen in Fig. 4.10.

We use Bicron BC-420 scintillator, which provides extremely fast timing. The emission spectrum is presented in Fig. 4.11. We use a Hamamatsu R1828 phototube, which has a 2 in diameter photocathode. The photocathode spectral response can be seen in Fig. 4.11.

Based on Fig. 4.11 I have taken 20% for the quantum efficiency, which takes into account a few percent for losses between interfaces. The expected number of photoelectrons can then be determined. In Fig. 4.12(a) I simulate minimum ionizing pions into the scintillator. The pions are generated isotropically at the target center. As the particles track through the scintillator, the energy deposited is weighted by the collection efficiency. Thus, when multiplied by the quantum efficiency we determine an expected number of photoelectrons. Fig. 4.12(b) is energy deposited in the scintillation array for the same events as Fig. 4.12(a). This illustrates that the distribution is broadened by the different collection efficiencies from particles hitting the scintillator.
1000 Au+Pb Minbias Events — Full Geometry

Figure 4.10: Distribution of fractional solid angles for 1000 Au+Pb minbias events.
Figure 4.11: (a) Emission spectrum for BC-420 (b) Photocathode Spectral Response for the R1828. Follow curve A (glass)
at different locations transverse to the beam.

In Fig. 4.13 I plot the number of photoelectrons we expect to see versus impact parameter for Au+Pb (that is, Fig. 4.8 with the solid angle and collection efficiency taken into account).

We wish to make a N(PE) (number of photoelectrons) cut so that we accept approximately 10% of the events. To select the 10% most central events, we impose a N(PE) (number of photoelectrons) centrality cut. Fig. 4.14 shows the distribution of impact parameters that pass this cut and the probability that an event with a particular impact parameter passes the N(PE) cut. In addition a 10% cut, a 5% and 1% cut are also shown.

Thus, we see a reasonable amount of light (at least 170 PE per counter for central events). In addition, from Fig. 4.14 it is clear that the efficiency of the counter is not affected by blackening the scintillator and light guide.

4.3.4 E864 Trigger

In the E864 experiment, a valid central interaction pretrigger is satisfied if two criteria are met: (1) The summed pulse height from the energy deposited in the four counters is above some threshold \( E_{\text{dep}}^{\text{tot}} > E_{10\%} \); (2) Each individual counter's pulse height is above some minimum threshold \( E_{\text{dep(i)}} > E_{\text{min}} \), where \( i \) represents each individual counter and goes from one to four. Note that in the experiment the INT-0 triggers did not have to meet this second requirement because it was found that the minimum available threshold of 10 mv on the discriminators we used was too high.

The first criteria selects central interactions, as discussed in Section 4. The second criteria vetoes false triggers. False triggers could come about from several sources: (1) \( \delta \)-ray interactions; (2) electronic noise; (3) upstream interactions. The minimum threshold on each counter is determined experimentally by running with no target, which we call an "empty" target.

With low minimum thresholds our selection of central events is not effected. However, as the minimum threshold is increased past about 15 minimum ionizing particles, central events begin to get vetoed. The effect of various minimum threshold cuts can be seen in Figs. 4.15 and 4.16.
Single Minimum Ionizing Particle Spectrum

Figure 4.12: (a) The number of photoelectrons from MIP particles. (b) $E_{\text{dep}}$ from MIP particles. 0.4 GeV $\pi^+$'s are generated isotropically at the center of the target.
Figure 4.13: Number of photoelectrons versus impact parameter for 1000 Au+Pb events. Full geometry.
Figure 4.14: 17,500 Au+Pb minbias events. Full geometry. Monte Carlo study of the centrality selection of the multiplicity counter. The three different curves represent different cuts on the number of photoelectrons expected in the multiplicity counter. The solid line represents a cut on the events with the 10% most photoelectrons, the dashed line represents the 5% most photoelectrons, and the dotted line represents the 1% most photoelectrons. (a) Distribution of impact parameters (in fm) which pass a 10%, 5% and 1% cut on the number of photoelectrons expected in the four scintillator counters in the multiplicity counter. (b) Trigger probability for a particular impact parameter event to pass a 10%, 5%, and 1% photoelectron cut. For the 10% cut $N(PE) > 755$. 

17,500 Au+Pb Minbias Events — Full Geometry

Figure 4.15: 17,500 Au+Pb minbias events. Full Geometry. The number of events passing the $E_{\text{dep}} > 0.35$ GeV and $E_{\text{dep}}(i)$ cut versus the $E_{\text{dep}}(i)$ cut. (1 MIP $\approx 0.002$ GeV). Note that in the 1994 run of E864, INT-0 triggers do not have a $E_{\text{dep}}(i)$ requirement.
17,500 Au+Pb Minbias Events -- Full Geometry

Figure 4.16: 17,500 Au+Pb minbias events. Full Geometry. The trigger probability for a particular impact parameter to pass the $E_{\text{dep}} > 0.35$ GeV and $E_{\text{dep}}(i) > 0.00, 0.04, 0.08,$ and .12 GeV. Note that in the 1994 run of E864, INT-0 triggers do not have a $E_{\text{dep}}(i)$ requirement.
4.3.5 Other Beam Particles and Targets

In addition to Au+Pb lead running, we may run with lighter projectiles and targets. This section is added for future reference. Readers may wish to skip to the next section (4.3.6) on a comparison between the Monte Carlo simulation and experimental data. With lighter projectiles and targets we expect fewer δ-rays to be produced. It is important to study how the shielding is affecting the central/peripheral discrimination.

Gold on Aluminum

Aluminum is the lightest target with which we plan to run. See Fig. 4.17 for the energy deposited into the interaction counter for 1000 δ-ray events. Thus, 4 times in 1000 events δ-rays fake a MIP. This is to be compared with the 14 times in 1000 events for Au+Pb. Fig. 4.18 is a scatter plot of $E_{\text{dep}}$ per event versus impact parameter for 1000 events. To select central events we impose a $E_{\text{dep}} > 0.08$ GeV cut so that we accept approximately 10% of the events. Fig. 4.19 is a plot of the distribution of impact parameters that pass the centrality cut. Fig. 4.19 gives the probability that an event with a particular impact parameter passes the $E_{\text{dep}}$ cut.

We must check that the discrimination is not being effected by the shielding. Fig. 4.20 is a scatter plot of $E_{\text{dep}}$ per event versus impact parameter for 1000 events. Fig. 4.21 is a plot of the distribution of impact parameters that pass a $E_{\text{dep}} > 0.15$ GeV centrality cut. Fig. 4.21 gives the probability that an event with a particular impact parameter passes the centrality cut. This demonstrates that the central/peripheral discrimination is not being compromised by the shielding. In Fig. 4.22 I plot the number of photoelectrons we expect to see versus impact parameter for Au+Al. The cut for the 10% most central is 185 PE or about 45 per counter.

Iodine on Lead

Iodine is the lightest projectile that we may run with.

See Fig. 4.23 for the energy deposited into the interaction counter for 1000 δ-ray events. Twelve times in 1000 events δ-rays fake a MIP. This is to be compared
1000 Au–Al $\delta$–ray Events -- Full Geometry

Figure 4.17: Total Energy deposited in GeV into the scintillation array for 1000 gold nuclei passing through a 10% aluminum target without interacting. Note that there is one entry per counter per event, or four per event. The geometry includes the target, vacuum pipe, shielding, and scintillator.
Figure 4.18: Correlation between $E_{\text{dep}}$ and impact parameter for 1000 Au+Al events. Full geometry.
Figure 4.19: 1000 Au+Al minbias events. Full geometry. (a) Distribution of impact parameters which pass a $E_{\text{dep}} > 0.08$ GeV cut. (b) Trigger probability for a particular impact parameter event to pass the $E_{\text{dep}} > 0.08$ GeV cut.
Figure 4.20: Correlation between $E_{\text{dep}}$ and impact parameter for 1000 Au+Al events. Geometry includes ONLY the target and scintillator.
Figure 4.21: 1000 Au+Al minbias events. Geometry includes ONLY the target and scintillator. (a) Distribution of impact parameters which pass a $E_{\text{dep}} > 0.15$ GeV cut. (b) Trigger probability for a particular impact parameter event to pass the $E_{\text{dep}} > 0.15$ GeV cut. Geometry includes ONLY target and scintillator.
1000 Au+Al Mínbias Events —— Full Geometry

Figure 4.22: Number of photoelectrons versus impact parameter for 1000 Au+Al events. Full geometry.
1000 I+Pb δ-ray Events —— Full Geometry

Figure 4.23: Total Energy deposited in GeV into the scintillation array for 1000 Iodine nuclei passing through the 10% lead target without interacting. Note there is one entry per counter per event, or four per event. The geometry includes the target, vacuum pipe, shielding, and scintillator.
with the 14 times in 1000 events for Au+Pb. Fig. 4.24 is a scatter plot of $E_{\text{dep}}$ per event versus impact parameter for 1000 events. To select central events we impose a $E_{\text{dep}} > 0.31$ GeV cut. Fig. 4.25a is a plot of the distribution of impact parameters that pass the centrality cut. Fig. 4.25b gives the probability that an event with a particular impact parameter passes the centrality cut.

We must check that the discrimination is not being effected by the shielding. Fig. 4.26 is a scatter plot of $E_{\text{dep}}$ per event versus impact parameter for 1000 events. Fig. 4.27 is a plot of the distribution of impact parameters that pass a $E_{\text{dep}} > 0.69$ GeV centrality cut. Fig. 4.27 gives the probability that an event with a particular impact parameter passes the centrality cut. This demonstrates that the central/peripheral discrimination is not being effected by the shielding.

In Fig. 4.28 I plot the number of photoelectrons we expect to see versus impact parameter for Au+Pb. The cut for the 10% most central is 668 PE or about 167 per counter.

### 4.3.6 Comparison With Experimental Data

The photoelectron distribution that the Monte Carlo program produces should look similar to the pulse height spectrum seen in the experiment. A comparison between these distributions provides a good test for the validity of the Monte Carlo simulations. In Fig. 4.29 we compare the the experimental ADC spectrum with the number of photoelectrons as simulated in the Monte Carlo. (See Chapter 6 for a discussion on the calibrations of the beam counters.) For the experimental data, a cut on the 10% highest ADC values for minbias events is shown in Fig. 4.29(a). For the Monte Carlo data, a cut on the events with the 10% most number of photoelectrons is shown in Fig. 4.29(b). Fig. 4.29 illustrates that the Monte Carlo program is in good agreement with the experimental data. We note that the program predicts an average of 950 photoelectrons for the four counter multiplicity counter for events with the 10% most photoelectrons.
1000 I+Pb Minbias Events — Full Geometry

Figure 4.24: Correlation between $E_{\text{dep}}$ and impact parameter for 1000 I+Pb events. Full geometry.
Figure 4.25: 1000 I+Pb minbias events. Full geometry. (a) Distribution of impact parameters which pass a $E_{\text{dep}} > 0.31$ GeV cut. (b) Trigger probability for a particular impact parameter event to pass the $E_{\text{dep}} > 0.31$ GeV cut.
1000 I+Pb Minbias Events —— No Shielding

Figure 4.26: Correlation between $E_{\text{dep}}$ and impact parameter for 1000 I+Pb events. Geometry includes ONLY the target and scintillator.
Figure 4.27: 1000 I+Pb Events. The geometry includes ONLY the target and scintillator. (a) Distribution of impact parameters which pass a $E_{\text{dep}} > 0.69$ GeV cut. (b) Trigger probability for a particular impact parameter event to pass the $E_{\text{dep}} > 0.69$ GeV cut.
1000 I+Pb Minbias Events — Full Geometry

Figure 4.28: Number of photoelectrons versus impact parameter for 1000 I+Pb events. Full geometry.
Figure 4.29: Comparison of the ADC spectrum from experimental data with the number of photoelectrons obtained from the Monte Carlo program. (a) Experimental ADC spectrum for minbias events with the 10% highest ADC values. (b) Monte Carlo photoelectron distribution for events with the 10% most photoelectrons.
Chapter 5

Occupancy Study

5.1 Introducion

The desire for a open geometry spectrometer and the design of the E864 vacuum chamber lead to a large number of interactions which shower the detectors with hits that are not associated with tracks coming from the target. Instead, these hits come from the interaction products of particles which hit the vacuum chamber walls, ribs, and flanges.

A GEANT simulation with a detailed description of the E864 geometry was used to determine where these hits come from and to aid in designing a plug to shield these areas.

It is desirable to keep the detector occupancies as low as possible in order to have a high tracking efficiency, and to reduce one's susceptibility to backgrounds. If a hodoscope slat which a real track goes through is hit by another particle, the timing and/or pulse-height information will be erroneous. One can make a simple estimate of the tracking efficiency:

$$\text{Tracking Efficiency} = (1-\alpha)(1-\beta)(1-\gamma)$$

where $\alpha$, $\beta$, and $\gamma$ are the occupancies in H1, H2, and H3 detectors. Thus, if the occupancies are 10%, the tracking efficiency due to occupancy is 73%, while if the
occupancies are 30% the tracking efficiency is 34%. The goal is to keep the occupancies below 10%.

5.2 Comparisons Between Monte Carlo Results And 1994 Data

The geometry used in the GEANT simulation is shown in Fig. 5.1. The geometry includes the vacuum chamber walls, the ribs on the bottom of the vacuum chamber (for the sides and top a rib averaged thickness is added to the vacuum chambers wall thickness), and the flanges between the vacuum chamber sections. HIJET was used to simulate 11.71 GeV/nucleon Au+Au collisions.

The effect of our interaction counter was taken into account by factoring in the trigger probability for a particular impact parameter (see Fig. 4.9) to pass our 10% highest pulse height cut. The selection of impact parameters is important because there is a correlation between the impact parameter and the number of hits from particles which do not come from the target (or background hits) in our geometry. In very peripheral interactions, the energy goes forward in a narrow cone and does not hit the vacuum chamber. In very central interactions, where the nucleus completely breaks up, much of its energy is sent in the transverse direction. However, there exists a region in between where it is more likely to hit the bottom of the vacuum chamber and ribs, creating background hits.

Table 5.1 shows a comparison between 1994 data and the Monte Carlo. The data occupancies represent the number of slats for a given hodoscope which both the top and bottom ADCs are above zero-suppression threshold (which is 100 channels above pedestal). The Monte Carlo occupancies represent the number of slats that get hit (where hits are taken when a charged particle enters the scintillator) with default GEANT cuts.

The Monte Carlo simulation with no plug can be compared directly to the 1994 experimental data. The Monte Carlo slightly underpredicts the data. In the worst case ("+1.5T" H1) the Monte Carlo predicts 68% of the experimental occupancy.
Figure 5.1: Elevation view of the detector geometry as simulated by GEANT. Note that the scale is anamorphic.
Table 5.1: Detector hit multiplicities from Monte Carlo and Data. The numbers represent the number of hit hodoscope slats in a given plane.

<table>
<thead>
<tr>
<th>Field</th>
<th>Detector</th>
<th>Data 1994</th>
<th>Data 1995</th>
<th>Monte Carlo no plug</th>
<th>Monte Carlo plug</th>
<th>Monte Carlo perfect shield</th>
</tr>
</thead>
<tbody>
<tr>
<td>+1.50 T</td>
<td>H1</td>
<td>38</td>
<td>14.3</td>
<td>26</td>
<td>11</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>H2</td>
<td>26</td>
<td>13.2</td>
<td>21</td>
<td>11</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>H3</td>
<td>21</td>
<td>13.3</td>
<td>16</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>+0.75 T</td>
<td>H1</td>
<td>41</td>
<td>16.7</td>
<td>32</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td></td>
<td>H2</td>
<td>29</td>
<td>15.8</td>
<td>26</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td></td>
<td>H3</td>
<td>24</td>
<td>15.7</td>
<td>21</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>-0.45 T</td>
<td>H1</td>
<td>39</td>
<td>16.9</td>
<td>32</td>
<td>16</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>H2</td>
<td>27</td>
<td>15.4</td>
<td>25</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>H3</td>
<td>23</td>
<td>15.5</td>
<td>20</td>
<td>14</td>
<td>10</td>
</tr>
<tr>
<td>-0.75 T</td>
<td>H1</td>
<td></td>
<td>13.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>H2</td>
<td></td>
<td>12.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>H3</td>
<td></td>
<td>12.5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Some of this difference can be accounted for by lowering the GEANT energy cut. If we lower the energy cut the Monte Carlo predicts about 80% of the experimental occupancy. (For the purposes of the study we keep the GEANT default cuts in order to have the statistics we need to understand the nature of the background.)

In addition to the overall occupancy numbers, the occupancy versus slat in a given detector can be compared in order to understand the differences between the Monte Carlo and data. The solid histogram in Fig. 5.2 shows the occupancy versus slat for $H_1$ with $B=+1.5T$ for the 1994 data. The solid line in Fig. 5.3 shows the occupancy versus slat at $H_1$ with $B=+1.5T$ for the Monte Carlo simulation with no plug. It can be seen that the shapes of the two distributions are quite different. Careful examination of the Monte Carlo data shows a two peak structure (one near the neutral line around slat 35 due to neutrons, and one toward the bend side around slat 125 due to protons) with a dip between the two peaks. Some indication of this structure can be seen in Fig. 5.3, and the structure is slightly clearer in Fig. 5.4, which shows the occupancy versus slat at $H_3$ with $B=+1.5T$ for the Monte Carlo data. In comparison, the data shows only one peak in the region where the Monte Carlo shows a dip. The differences between these shapes is believed to arise from the limitations of the event generator. In particular, it seems likely that the background is caused by fragments or coalesced nuclei which have a $Z/A$ between 0 and 1 hitting the bottom of the vacuum chamber and ribs.

One thing to note is the structure in 1994 data in Fig. 5.2. The light guides on the hodoscope alternate between upstream and downstream and stagger up and down. The structure we see repeats every four channels. Thus, it is consistent with background particles hitting the upper light guides and phototubes and scintillator slat.

Although there are differences between the Monte Carlo and data we believe that the nature and cause of the background hits are the same. This should become clearer in the next section. Thus, the Monte Carlo was deemed adequate to study where the background comes from and to design a plug to eliminate a large fraction of this background.
Figure 5.2: Occupancy versus slat at H1 with B=+1.5T for 1994 data (solid line) and 1995 data dotted-dashed line.
Monte Carlo Data for H1, $B = +1.5T$

Figure 5.3: Occupancy versus slat at H1 with $B = +1.5T$ for the Monte Carlo simulation. The solid line includes the geometry as it was for the 1994 run – with no plug; the dashed line includes the plug; the dotted line is the occupancies if the shielding were perfect.
Figure 5.4: Occupancy versus slat at H3 with B=+1.5T for the Monte Carlo simulation. The solid line includes the geometry as it was for the 1994 run – with no plug; the dashed line includes the plug; the dotted line is the occupancies if the shielding was perfect.
Table 5.2: Source of charged particles which hit H1 and do not come from the target.

<table>
<thead>
<tr>
<th>Source</th>
<th>% of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom</td>
<td>75%</td>
</tr>
<tr>
<td>Window</td>
<td>8%</td>
</tr>
<tr>
<td>Side</td>
<td>6%</td>
</tr>
</tbody>
</table>

5.3 Where Does The Charged Background Come From?

Qualitatively, one can look at a typical GEANT event to get an idea where the background hits are coming from. Fig. 5.5 shows a typical Monte Carlo event with no plug. If you study the hits in H1 it is evident that a large fraction of them are coming from the ribs and vacuum chamber wall above them. This is similarly true for the other detectors.

The source of the background was studied more quantitatively. GEANT was used to study where the background hits are coming from. In particular, the contributions to different parts of the vacuum chamber and shielding were studied. Table 5.2 shows the contribution to the charged background hits in H1. The bottom refers to a combination of the bottom of the vacuum chamber and the vacuum chamber ribs. The window is the upstream window, and the side is the side of the vacuum chamber. The remaining 10% come from the collimator in M1, the rest of the vacuum chamber, and other random interactions in the air and detectors. From Table 5.2 we concluded that it is sufficient to shield the lower vacuum chamber wall, ribs, and flanges with an upstream plug.

5.4 The Plug

The location of the plug can be seen in Figs. 2.3 and 5.1. It is 50cm (> 3\(\lambda_i\) - proton nuclear interaction lengths) thick and made of brass. It is located between the two magnets. This location is far enough from S2 and H3 and is separated by a magnet to sweep away soft particles produced in the brass. In addition, it is located
Figure 5.5: Typical central Au+Au interaction tracked by GEANT through the E864 apparatus. Dashed or dotted are neutral particles. Particles are allowed to interact with the shielding. The geometry does not include the plug. See Fig. 5.1 for the layout. Note that the scale is anamorphic.
far enough away from $S_1$ so as not to increase $S_1$'s occupancy by a significant level (from albedo). The top of the plug is designed to shield as much of the bottom of the vacuum chamber as possible while abiding by our beam stay clear. The bottom is defined by our experimental acceptance. In the direction transverse to the beam it fills the entire section of the vacuum chamber.

Fig. 5.6 shows a typical Monte Carlo event with the plug. Comparing with Fig. 5.5 it is clear that the plug has the desired effect.

Table 5.1 shows quantitatively the effects of the plug (see the Monte Carlo (plug) column). This table also shows the the situation where one has perfect shielding (all particles are stopped when entering the vacuum chamber, collimator, ribs, and flanges). The solution with the plug approaches the perfect solution.

Figs. 5.3 and 5.4 show the occupancy versus slat distributions in $H_1$ and $H_3$ for the following cases: (a) no plug; (b) plug; and (c) perfect shielding.

### 5.5 1995 Data

The plug was installed for the 1995 run, and as a result the occupancies of the detectors were dramatically reduced. A comparison between the 1995 and 1994 data is shown in Table 5.1 and Fig. 5.2. These occupancies are now below the design goal of 10% per plane.
Figure 5.6: Typical central Au+Au interaction tracked by GEANT through the E864 apparatus. Dashed or dotted are neutral particles. Particles are allowed to interact with the shielding. The geometry includes the plug. See Fig. 5.1 for the layout and Fig. 5.5 for the simulation with no plug. Note that the scale is anamorphic.
Chapter 6

Calibrations

The detectors were calibrated in order to translate the raw digitized ADC and TDC values into meaningful physics quantities. In this chapter I describe how the following counters were calibrated for the strangelet analysis:

- **Beam Counters.** MITCH is calibrated to select single beam events and to determine the reference time (T0) for our hodoscope time-of-flight measurements. MULT is calibrated to get information on the centrality of the interactions, and to get a rough timing measurement.

- **Hodoscopes.** The hodoscopes are calibrated to measure the charge, time-of-flight and vertical position of particles which traverse each hodoscope plane.

- **Calorimeter.** The calorimeter is calibrated to measure the deposited energy and time-of-flight of incident particles. For the strangelet analysis, the calorimeter is used to study whether high mass strangelet candidates which strike the calorimeter are consistent with strangelets.
Figure 6.1: 60 Hz noise on the uncalibrated MULT-A ADC Pedestal

6.1 Beam Counters

6.1.1 Pulse Height Calibration

The pulse height spectrum of the MULT and MITCH counters are susceptible to noise. The amount of noise in the ADC spectra can be seen in its ADC pedestal width. A large portion of its noise is in phase with the 60 Hz AC power. Because we record the phase of the 60 Hz AC a correction can be made to sharpen up the pulse height spectra.

MULT

The MULT detector consists of four counters: MULT-A, MULT-B, MULT-C, and MULT-D. The pulse height from the MULT detector provides information on the centrality of the interactions. Therefore, it is useful to correct its pulse height.

Fig. 6.1 shows the pedestal pulse height in MULT-A versus the 60 Hz clock. A clear correlation can be seen. Thus, a correction can be made to reduce the pedestal width because we record the phase of the 60 Hz power for each event. To make the
Figure 6.2: Comparison between 60 Hz corrected non-60 Hz corrected MULT-A ADC pedestal.

60 Hz correction, I divide up the 60 Hz clock into 100 bins. Then, for each bin in time I create a look-up table by taking ADC average for pedestal events. A bin-by-bin correction is then made by subtracting off the ADC average for that 60 Hz bin, thus performing a pedestal and 60 Hz correction at the same time. The effect of the 60 Hz correction on the pedestal width can be seen in Fig. 6.2. The 60 Hz/pedestal correction is made separately for the phototubes.

A plot of the calibrated pulse height distribution from MULT of the minimum bias trigger is given in Fig. 6.3. The histogram represented by the dotted lines represents the pulse height spectrum for Central triggers. Only Central triggers are used for the strangelet analysis, as it is believed that a strangelet is far more likely to be formed in the most central collisions.

MULT was calibrated each run.

MITCH

The MITCH detector contains two phototubes: MITCH-A and MITCH-B. For the strangelet analysis, the pulse height spectrum from the sum of the two MITCH
counters is used to select events in which only one beam particle goes through MITCH within our gate. In addition, the pulse height spectrum is used in conjunction with the time spectrum to make the MITCH slew correction.

The MITCH pulse height spectrum is calibrated in the same way as the MULT counter. The 60 Hz/pedestal correction is made separately for the two MITCH phototubes. The calibrated pulse height spectrum for MITCH at a beam rate of $1.2 \times 10^7$ Au ions per second can be seen in Fig. 6.1.1. A clear separation between single, double, quadruple, and even quintuple beam particles can be seen. Note that for the data that I will discuss, we ran at a much lower beam rate ($3.0 \times 10^5$), and therefore the double-beam particle contribution is much less. The calibrated pulse height spectrum for MITCH at a beam rate of $3.0 \times 10^5$ Au ions per second can be seen in Fig. 6.5. The double beam cut at a calibrated pulse height of 1100 is shown on the figure. 1.5% of triggers in Fig. 6.5 have a calibrated pulse height greater than the cut. This cut is applied in 1994 "B=+1.5T" analysis.

MULT was calibrated each run.
High Rate MITCH Pulse Height Spectrum

![High Rate MITCH Pulse Height Spectrum](image)

Figure 6.4: Calibrated pulse height spectrum of the beam counter at an incident beam rate of \(1.2 \times 10^7\) Au ions per second.

Low Rate MITCH Pulse Height Spectrum

![Low Rate MITCH Pulse Height Spectrum](image)

Figure 6.5: Calibrated pulse height spectrum of the beam counter at an incident beam rate of \(10^6\) Au ions per second. The line represents a double beam cut.
Figure 6.6: Uncalibrated MITCH-A TDC vs. Calibrated ADC. The solid lines are the bin-by-bin slew corrections.

6.1.2 Time Calibration

Because the signals from the same type of phototube have similar shapes regardless of their amplitude, large pulse heights will fire a fixed threshold discriminator before small pulse heights. This is known as a slewing effect, and can be corrected for because we record the pulse heights. The slew correction is made in a similar way to the 60 Hz correction: I divide up the 60 Hz corrected ADC value into 100 bins. Then, for each bin in time I create a look-up table by taking the TDC average. See Fig. 6.6 for an example of the slewing of the MITCH-A counter. The line represents the bin-by-bin slew correction. A bin-by-bin correction is then made, performing the slew correction. The slew correction is made separately for the two MITCH and four MULT phototubes.

The slew curve fit is performed for a particular range of ADC and TDC values. For the 1994 run the slew fits included the following cuts.

- **MITCH-A and MITCH-B:** $150 < \text{ADC} < 800$ Cut on calib ADCs.
- **MITCH-A:** $2630 < \text{TDC} < 2680$; **MITCH-B:** $2630 < \text{TDC} < 2680$ Cut on
raw TDCs.

- (MITCH-A+MITCH-B)<3000 Cut on high MITCH raw ADCs.

For the strangelet analysis, the cut on the MITCH raw ADCs (MITCH-A+MITCH-B) was set to 2200 to eliminate double beam events. All the cuts amount to cutting out 2.5% of the data over all the “B=+1.5T” runs.

Because we do not have a second counter with comparable resolution, we cannot measure the time resolution of MITCH directly. However, because we have two tubes on MITCH, we can deduce the resolution if we assume that both tubes have the same resolution, and if we assume that the particles strike the center of the counter:

$$
\sigma(T_0) = \sigma\left(\frac{T_A + T_B}{2}\right) = \frac{1}{2} \sqrt{\sigma^2_{T_A} + \sigma^2_{T_B}} = \frac{1}{2} \sigma(T_B - T_A)
$$

(6.1)

Note that the transit time contribution from a 3mm spot size spread is about 20ps.

This resolution for the raw and calibrated MITCH can be seen in Fig. 6.7 as a function of run number. The average calibrated resolution is about 80ps. The odd bump around run number 100 in the uncalibrated data is not completely understood. It is possible that the slewing became more important for those runs because of where the beam hit in MITCH or because of contamination on the surface of the MITCH counter. This would lead to a worse uncalibrated time resolution, but the similar calibrated time resolutions.

Note that the above slew correction is not totally correct, because we can not separate the slew in the MITCH counters with the slew in the gate. Ideally we would like to correct for only the slew in the MITCH counters. This is not a limitation for the analysis of the 1994 run; however, it was found to be important for the 1995 run [54] because of larger slewing corrections due to the damage incurred on the MITCH plate.

MITCH was calibrated each run.
Figure 6.7: Raw and Calibrated MITCH time resolution vs run number.

6.2 Hodoscopes

The three hodoscopes planes encompass a total of 618 slats and 1236 phototubes. Each slat is calibrated to produce a charge-space-time point.

We subdivide the calibrations into those which can be done without tracking (pass 0), and those which require tracking (pass 1). See Sec. 7.1 for a description of tracking. The pass 0 calibrations are performed for each run, while the pass 1 calibrations have one set of constants for the complete "+1.5T" data sample.

The charge is determined by performing a gain correction on the pedestal subtracted ADCs (Eq. 6.15). The pedestal correction is a pass 0 calibration, while the charge calibration is a pass 1 calibration.

The TDCs need to ultimately be converted to give the actual time $t$ that it took a particle to go from the target to a given hodoscope slat, as will be explained. The time-of-flight is determined from the time zero offsets and slew corrected TDC values, which have been corrected for run to run variations (Eq. 6.19). The run to run variations are taken care of by the slew time offset procedure which is discussed in the next section, while the ultimate slewing curve and time zero offsets are determined
in pass 1 calibrations.

The $y$-position is determined from the vertical offsets, corrected TDC values, and measured index of refraction. (Eq. 6.17). The vertical offsets and effective index of refraction are determined in pass 1 calibrations.

### 6.2.1 Pass 0 Calibrations

The pass 0 calibrations take into account the run-by-run variations.

#### Bad Channel Finder

There were a small number of bad hodoscope channels for the 1994 run. These channels had, for example, bad headers on cables, bad bases, or bad TDC channels. These changed run to run, as some channels were repaired during the run, and others broke. A pass was made through the data, and if a slat passed any of the following criteria it was placed in the bad channel list for a given run:

- **No Hits** The slat records no hits for the entire run.

- **Low Occupancy** The slat's top or bottom ADC or TDC records an abnormally low occupancy compared to that of the other top or bottom ADC or TDC.

- **Uncorrelated ADCs or TDCs** The top and bottom ADCs or TDCs are not correlated.

Overall, there are an average of about 5 bad channels per run for all 3 hodoscopes. A new bad channel list is made for each run.

#### Pedestal Finder

During the 1994 data run we took separate runs in which the hodoscopes were not zero-suppressed in order to determine the pedestals of each hodoscope channel. One of these runs was done before each data run. The pedestals were determined in the following way:

1. Choose runs with no ADC zero suppression.
2. Require the no-hit criterion: no TDC hits from slat (either top or bottom PMT); 
   $400 < \text{ADC} < 800$ counts.

3. Determine mean $\mu_0$ and RMS width $\sigma_0$ of the ADC distribution.

4. Cut on $| \text{ADC} - \mu_0 | < 4\sigma_0$. (This eliminates spurious high and low ADC 
   readings).

5. Determine new mean $\mu$ and RMS $\sigma$.

A detailed study of the hodoscope pedestals was performed[55]. The conclusions 
of the study are as follows:

- Roughly 90% of the channels have pedestal RMS's less than 10 channels. The 
  remaining 10% tend to be non-Gaussian distributions with typical RMS's up to 
  30 channels. These wider pedestals are due to poor ground connections.

- Variations within a run are small.

- No correlation between the ADC pedestal and the 60 Hz clock was observed.

The pedestal corrected top and bottom ADCs are given by:

$$
\begin{align*}
\text{adc\_top\_ped} &= (\text{raw\_adc\_top} - \text{ped}) \\
\text{adc\_bot\_ped} &= (\text{raw\_adc\_bot} - \text{ped})
\end{align*}
$$

(6.2)

where PED is different for each phototube.

The pedestals for the hodoscopes are determined separately for each data run.

Slew Time Offsets

The slew time offsets are the key to the our calibration scheme. They are designed to 
take care of the run to run variations of the time calibration. In order to determine 
the slew time offsets for a particular run, the pedestals must first be determined, and 
the slew curve must be known. For this discussion, I assume that we already know 
how to make the slew correction. See Sec. 6.2.2 for more information on the slew 
correction.
Fig. 6.8 shows a comparison of one slat on H1 between two different runs. A shift of approximately 11 TDC channels, or 550 ns, can be seen. The TDCs can drift from run to run due to temperature changes. Changes in temperature affect the lengths of the cables, and thus the time the signals arrive in the counting house. It is found that, although they may drift, the shape of the TDC distributions are similar from run to run. The TDC distributions are dominated by the real time distributions of the particles hitting a given hodoscope slat. The shape of the TDC distribution is not too sensitive to the other factors, such as the beam tune. It is easiest to make a reliable correction if a gross feature of the distribution can be fit. A peak is expected for each slat because a particular particle species tends to dominate the time distribution. For part of the detector this might be pions, while for other parts of the detector it may be protons. Further, for each slat there is a limited range in rapidity and transverse momentum for which a particular particle species can strike a particular slat. The sharper the peak the more reliable the fit to the peak will be. Therefore, effort is made to make the peak as sharp possible because a sharper peak will yield a more reliable fit. To sharpen up the peak, a slew correction is applied, and the particles are constrained to lie within a small region of the slat to reduce transit time effects.

After the slew correction and position requirements are made, the distributions are well peaked. The position requirement is:

\[ | \log(\text{adc\_top\_ped}/\text{adc\_bot\_ped}) | < 0.1 \]  \hspace{1cm} (6.3)

This selects hits which are located in a particular region of the slat:

\[
\begin{align*}
\text{adc\_top\_ped} & = C_1 \times e^{-(L+y)/\lambda} \\
\text{adc\_bot\_ped} & = C_2 \times e^{-(L-y)/\lambda}
\end{align*}
\]  \hspace{1cm} (6.4)

where \( y \) is the distance from where the particle passes through the scintillator to the center of the slat, \( 2L \) is the length of the scintillator slit, \( \lambda \) is the attenuation length of the scintillator material, \( C_1 \) and \( C_2 \) are the amplitudes, \( \text{adc\_top\_ped} \) and \( \text{adc\_bot\_ped} \) are the pedestal subtracted top and bottom ADCs. The attenuation length of the scintillators is \( \lambda = 130 \) cm. From Eq. 6.4 we derive

\[
\log \left( \frac{\text{adc\_top\_ped}}{\text{adc\_bot\_ped}} \right) = -\frac{2y}{\lambda} \log \frac{C_1}{C_2}
\]  \hspace{1cm} (6.5)
Figure 6.8: A comparison between the slew Corrected TDC distributions in TDC channel numbers (50 ps per channel) of H1 slat 100 top, with the position requirement $|\log \left( \frac{adc_{\text{top ped}}}{adc_{\text{bot ped}}} \right) | < 0.1$ from runs 55 and 255. The time shift between the two runs is about 11 channels, or 550 ps.

If the tubes were perfectly gain matched ($C_1 = C_2$), the log of the ratios is zero when particles pass through the center of the slat. However, the raw values are only roughly gain matched. From Eqs. 6.3 and 6.5 this requirement means that the vertical position is a region 13 cm long near the center of the slat.

The goal of the slew time offsets is to take out overall shifts in the TDC distributions for each tube from run to run. This is accomplished by offsetting the distributions for each tube to a fixed place. All the slew corrected TDC distributions with the position cut, as shown in Fig. 6.9, are fit to the sum of two Gaussian distributions. The first Gaussian is constrained to fit the peak, and the second Gaussian is constrained to fit the tail. This TDC distribution is well fit by this as can be seen in Fig. 6.9, where the distribution is fit to:

$$\frac{dN}{d(TDC)} = P1 \times e^{-\frac{(x-P2)^2}{2(P3)^2}} + P4 \times e^{-\frac{(x-P5)^2}{2(P6)^2}}$$

(6.6)

This function was found to yield the most consistent results. See [37] for further details. The parameter $P2$, which is the center of the Gaussian distribution which
Figure 6.9: Slew Corrected TDC distribution in TDC channel numbers (50 ps per channel) of H2, slat 100 bottom, with $|\log(\frac{\text{adc\_top\_ped}}{\text{adc\_bot\_ped}})| < 0.1$ The fit is to two Gaussian distributions: one which fits the peak, and one which fits the tail. P2, the mean of the Gaussian which fits the peak, is the slew time offset for this tube.

fits the peak, is the slew time offset.

We can now calculate the slew and slew time offset corrected tdc values.

\[
\begin{align*}
\text{tdc\_top}(\text{ns}) &= (\text{raw\_tdc\_top} - (\text{slew\_toff} + \text{slew})) \times \text{tdc\_scale} \\
\text{tdc\_bot}(\text{ns}) &= (\text{raw\_tdc\_bot} - (\text{slew\_toff} + \text{slew})) \times \text{tdc\_scale}
\end{align*}
\]  

(6.7)

where \text{raw\_tdc\_top}, \text{raw\_tdc\_bot} are the raw uncalibrated TDCs in fastbus channels, \text{slew\_toff} is the slew time offset (there is a different correction for each tube), \text{slew} is the slew correction (which is a function of \text{adc\_top}), and \text{tdc\_scale} is the number of ps per TDC channel (50 ps/channel for the 1994 run).

The quality of the slew time offset calibration is evaluated by looking at the mean time distributions, where the mean time of a given scintillator slat is given by

\[
\text{hodo mean time} = \frac{(\text{tdc\_top} + \text{tdc\_bot})}{2}
\]  

(6.8)

The mean time is a useful quantity to consider when discussing the time that the
Figure 6.10: Mean time distribution of a single hodoscope slat (H2, slat 100, run 56). A Gaussian fit gives us the mean time peak. In this case, the mean is 0.02 ns, and the sigma is 0.269 ns.

Particles passes through the scintillator slat because it takes out any positional dependence due to transit time. This can be seen as follows:

\[
\begin{align*}
tdc_{\text{top}} &= \frac{L - y}{v} \\
tdc_{\text{bot}} &= \frac{L + y}{v} 
\end{align*}
\]  \hspace{1cm} (6.9)

where \(2L\) is the length of the scintillator slat, \(y\) is the position from the center of the slat, and \(v = \frac{n}{c}\) is the speed of light in scintillator (\(c\) is the speed of light in vacuum, \(n \approx 1.9\) is the index of refraction of scintillator determined during pass1 calibrations), and \(tdc_{\text{top}}\) and \(tdc_{\text{bot}}\) are given by Eq. 6.7. Thus,

\[
hodo \text{ mean time} = \frac{n}{c} L 
\]  \hspace{1cm} (6.10)

Fig. 6.10 gives the mean time distribution for one slat on the H2 detector. Each slat is fit to a Gaussian distribution, and the center of the Gaussian is taken as the mean time peak. Then, the mean time peak value of the 206 slats on a given detector can be plotted. See Fig. 6.11. Note that the RMS of the distributions is less than 50 ps
Figure 6.11: Mean time peak distribution for the H2 detector (Run 56). The mean of the distribution is 0.0012 ns, and the RMS is 0.025 ns.

(one tdc count). This is important to monitor because the spread in mean times due to the slew time offset calibration contributes to the time resolution.

6.2.2 Pass 1 Calibrations

Once the pass 0 calibrations have been completed, the constants which allow us to determine the charge, vertical position, and time can be determined. The pass 1 calibrations require tracking, and generally only one calibration is required for each field setting. The calibrations used for all the “+1.5T” runs for the 1994 run are a combination of four runs which are distributed throughout the running time.

Charge Calibrations

A scintillation counter takes advantage of the fact that charged particles which pass through scintillator deposit energy due to ionization. A fraction of this energy goes into exciting atoms in the scintillating medium. Some of the energy when the atoms de-excite goes into producing light which has a wavelength within the sensitivity
of the photomultiplier tube. The tube's signal is then digitized by an ADC. This digitized pulse is proportional to the ionization energy lost in the scintillator.

The expression for the mean rate of energy loss due to ionization for moderately relativistic charged particles is given by the Bethe-Block formula\[56\]:

\[
\frac{dE}{dx} = D_e \left( \frac{Z}{\beta} \right)^2 n_e \left[ \ln \left( \frac{2m_e c^2 \beta^2 \gamma^2}{I} \right) - \beta^2 \right]
\]

(6.11)

\[D_e = 4\pi r_e^2 m_e c^2 = 5.0989 \times 10^{-25} \text{MeV cm}^2\]

\[r_e = \frac{e^2}{m_e c^2} = 2.8179 \times 10^{-13} \text{cm}\] is the classical radius of the electron, \(m_e = 0.511 \text{MeV}/c^2\) is the mass of the electron, \(c = 2.9979 \times 10^{10} \text{ cm/sec}\) is the speed of light, \(Z\) is the average nuclear charge of the incident particle, \(n_e = z \frac{N_A \rho}{A} = 3.1 \times 10^{23}/\text{cm}^3\) is the number of electrons per cubic centimeter in the scintillator (where \(z = 5.612\) is the charge of the scintillator, \(N_A = 6.02 \times 10^{23}\) atoms/mol is Avogadro's number, \(\rho = 1.032 \text{ g/cm}^3\) is the density of scintillator, and \(A = 11.157\) is the atomic weight of the scintillator), \(I = 64.7 \text{ eV}\) is the mean ionization potential of the scintillator, \(\beta = v/c\) of the incident particle, and \(\gamma = \frac{1}{\sqrt{1-\beta^2}}\).

From Eq. 6.11 we can see that the energy loss, and thus the ADC value, is proportional to the \(Z^2\) of the ionizing particle. Thus, from the pulse-height spectrum we can resolve the charge of the particle.

The charges are calibrated with the use of all tracked particles. When we consider tracks with all \(\beta\)'s, they are almost all charge one. Since we know both the \(y\)-location of the hit on the slat from tracking and we the \(y\)-location of the center of the slat from survey, we can correct the pedestal subtracted ADCs for attenuation length. This allows us to get more statistics by including all hits in a slat. We calculate what we would expect the ADC value to be if it hit the center of the hodoscope slat. This is done as follows:

\[
\text{adc.corr.top} = \text{adc.top.ped} \times e^{+y/\lambda} \\
\text{adc.corr.bot} = \text{adc.bot.ped} \times e^{-y/\lambda}
\]

(6.12)

where \(y = 0\) is the middle of the slat. For each tube, the ADC attenuation length corrected and pedestal subtracted is plotted. The peak of each distribution is used as the gain correction. See Fig. 6.12.
Figure 6.12: ADC pulse-height distributions for one tube on a hodoscope slat. The dashed histogram is the pedestal subtracted ADC spectrum, while the solid histogram is pedestal subtracted and attenuation length corrected ADC spectrum. The solid curve is fit to a Gaussian, and the mean of the Gaussian is used for the gain factor for that slat.
Figure 6.13: $Z^2$ distribution of the H2 detector. Charge 1, 2 Charge 1, and Charge 2 peaks can be seen.

The $Z^2$ of the particle is found by computing the geometric mean (GMADC) of the top and bottom phototubes. From Eq. 6.4, we can calculate the geometric mean of the top and bottom tubes:

$$GMADC = \sqrt{\text{adc}\_\text{top} \times \text{adc}\_\text{bot}} = \sqrt{C_1 \times C_2 \times e^{(-2\frac{Z}{\beta})}}$$

(6.13)

where

$$\text{adc}\_\text{top} = \left(\frac{\text{adc}\_\text{top}\_\text{ped}}{\text{gain}\_\text{top}}\right), \quad \text{adc}\_\text{bot} = \left(\frac{\text{adc}\_\text{bot}\_\text{ped}}{\text{gain}\_\text{bot}}\right)$$

(6.14)

The geometric mean is the correct quantity to use to measure the charge of the particle because it is does not depend on the position at which the particle enters the scintillator slat. Thus, we deduce the charge from the gain corrected geometric mean of the top and bottom tubes:

$$(\text{Charge})^2 = \sqrt{(\text{adc}\_\text{top}) \times (\text{adc}\_\text{bot})}$$

(6.15)

Fig. 6.13 shows the geometric mean distribution for the H2 detector. This plot is for tracks with $\beta < 0.985$ for the entire "+1.5T" data sample.
Vertical Position Calibrations

In addition to providing time information, a scintillator slat equipped with a top and bottom phototube can be used to deduce the vertical position of the particle. Because the signals from the two tubes run along different cables, and the tubes are not all run at identical voltages, the $y$-positions must be calibrated. From Eq. 6.9 we can see that one can get a measurement of the vertical position along a scintillator slat by taking the time difference of the top and bottom phototubes:

$$tdc_{\text{bot}} - tdc_{\text{top}} = \frac{n}{c} 2y$$  \hspace{1cm} (6.16)

The effective index of refraction is measured from tracking in an iterative procedure. The manufacturers value of $n = 1.58$ was used as input. This is close enough to the true value to get tracks, and to get a first pass $y$ offset calibration.

After a rough calibration is performed which is good enough to get tracks, the vertical positions can be calibrated using tracks. For the 1994, one knows the target and straw locations from survey data. Thus, we fit the track using only the target and the straws, and project its position to $H_1$, $H_2$, and $H_3$. Note that this fit is versus the pathlength of the track, which is calculated by the momentum reconstruction program. (See 7.1 for a discussion of the momentum reconstruction program.) The $y$-position residual is then taken for each slat of each hodoscope.

Fig. 6.14 shows a $y$-residual distribution of one $H_1$ slat.

The $y$-position of the hit on a scintillator can now be calculated:

$$y = \frac{c (tdc_{\text{bot}} - tdc_{\text{top}})}{n} - y_{\text{offset}} + y_0$$  \hspace{1cm} (6.17)

where $y_{\text{offset}}$ is the vertical calibration constant, and $y_0$ is the center of the slat in global coordinates determined from survey. There is one $y_{\text{offset}}$ constant for each scintillator slat.

Now that the $y$-positions have been calibrated, we can determine the effective index of refraction. Tracks are once again fit using only the target, straws, and their pathlengths. The fit is then projected to $H_1$, $H_2$, and $H_3$. A scatter plot of the $y$-position from tracking versus the $y$-position from the calibrated hodoscope slat should yield a straight 45° line if the index of refraction is correct. Fig. 6.15 shows
Figure 6.14: y-residual plot for one slat in the H1 detector. A line is fit from the target to the straw tube, and is projected to H1. The residual is fit to a Gaussian, in this case the mean = 4.84 cm, and the sigma = 2.96 cm. The y-position offset for this slat is thus determined: y_offset = -(mean).

Table 6.1: Effective index of refraction for H1, H2, and H3 as determined from the "B=+1.5T" data.

<table>
<thead>
<tr>
<th>Detector</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
<td>1.94</td>
</tr>
<tr>
<td>H2</td>
<td>1.87</td>
</tr>
<tr>
<td>H3</td>
<td>1.87</td>
</tr>
</tbody>
</table>
Figure 6.15: The vertical axis is the $y$ position from tracking, while the horizontal axis is the $y$-position from the calibrated hodoscope slat. The difference of a slope from a fit to this data compared to that of the $45^\circ$ line which drawn on the figure yields a correction to $n$.

such a plot for the H1 detector for $n = 1.58$. This distribution fits well to a straight line, but it is not at $45^\circ$. The $45^\circ$ line can be seen in the figure. A fit to Fig. 6.15 used to make a correction to the index of refraction. The new $n$ is then used as input, and the procedure iterates until it converges. This is done separately for the three hodoscopes. The results are summarized in Table 6.1 After this procedure was performed, a new $y$-position offsets were determined with the true values of the index of refraction.

The $y$ position calibration was done once, and used for the entire "+1.5T" 1994 data set.

Slew Curve

Because the slewing depends on the pulse shape, and all the scintillator slats on a hodoscope plane are attached to the same type of phototube, we expect the slew curve to be similar for all the slats in a given plane. There may be some differences from
plane to plane because the coupling between the scintillator slats and light guides are a bit different from plane to plane. Thus, we used three slew curves, one for each plane. We found the slew curve to fit the following functional form well:

\[
\text{slew} = a + \frac{b}{\sqrt{\text{raw}_{\text{adc}}}} + e^{c + dx(\text{raw}_{\text{adc}})}
\]  \hspace{1cm} (6.18)

It was an iterative process to create the first slew curve. This is because the slew curve is required for the slew time offsets. See [37] for further details on how this procedure was carried out.

Once an approximate slew curve is used and the slew time offset performed, the slew curve was refined as follows:

- The pedestal subtracted ADC value is calculated for each slat.
- The TDC with the slew time offset correction (see the previous section) is calculated. This allows all slats on a hodoscope plane to be overlayed, gaining statistics.
- The TDC value is adjusted to the center of the slat.
- The TDC vs. ADC plot is made
- This is fit to Eq. 6.18.

This was done for all three hodoscope planes separately.

The fit values for the hodoscopes are listed in Table 6.2.2, and the H2 slew curve is plotted in Fig. 6.16.

the slewing curve parameters for H1, H2, and H3 can be seen in Tab. 6.2.2

**Time Calibration - TZERO File**

We are now in a position to convert the actual time \( t \) that it took a particle to go from the target to a given hodoscope slat. The one remaining piece is to determine the time that it took the particles that formed the peak in the slew time offsets to travel
Figure 6.16: H2 Slew curve.

Table 6.2: Slewing curve parameters for H1, H2 and H3.

<table>
<thead>
<tr>
<th></th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
<td>-254.54</td>
<td>305.979</td>
<td>5.4336</td>
<td>-2.4 × 10⁻⁵</td>
</tr>
<tr>
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<td>-148.77</td>
<td>412.580</td>
<td>4.7237</td>
<td>-4.9 × 10⁻⁵</td>
</tr>
<tr>
<td>H3</td>
<td>-91.191</td>
<td>547.116</td>
<td>3.7200</td>
<td>-1.0 × 10⁻⁴</td>
</tr>
</tbody>
</table>

from the target to a particular hodoscope slat. We call these constants TZEROs, and they are used to calibrate the hodoscope time as given in the following formula:

\[
time = \frac{(tdc\_top + tdc\_bot)}{2} + \text{TZERO} - \frac{(\text{mitch}\_a + \text{mitch}\_b)}{2}
\]  

In the slats where we can identify particles which have a \( \beta < 0.985 \), the TZERO’s are determined using the known mass of the identified particle, and the reconstructed momentum of the particle:

\[
\beta = \frac{p/m}{\sqrt{1 + (p/m)^2}}
\]
\[ t_{\text{hodo}} = \frac{l}{\beta c} \]
\[ \text{TZERO} = t_{\text{hodo}} - \text{hodo mean time} \]  

where \( p \) and \( l \) are the momentum and pathlength of the reconstructed track, \( m \) is the true mass of the identified particle. Then, for each slat this TZERO distribution is fit to a Gaussian, and the mean of the Gaussian is the TZERO for that slat. We can get a TZERO from identified tracks from approximately hodoscope slat 60 to 206 for the "+1.5T" field setting.

The initial set of TZERO's was generated by the use of Monte Carlo. Particles generated with the distributions from the transport model RQMD. It was found that the actual TZERO's and those generated by the monte carlo only differed by one or two TDC channels (50-100 ps). The Monte Carlo values were used for the slats which do not see identified particles. These slats are important, because objects such as strangelets which have a low \( Z/A \) ratio will occupy this region of the detector. However, it is most crucial to actually discover that such a track exists, and not to get the best mass measurement. Thus, rough TZERO's are acceptable in this region. One would expect this region to be inhabited by mostly negative \( \nu \approx c \) pions. A further check that the TZERO's are reasonable was done by looking at the \( \beta \) distribution for all negative tracks in this region of the detector. It was peaked near one.

A plot of \( \beta \) versus H1 slat can be seen in Fig. 6.17. As one goes further to the side of the apparatus where positive particles bend (higher hodoscope slat numbers), the average value of velocity of the particles go down. On the negative bend side they are peaked around one. The neutral line is at slat 35.

Four runs, or approximately 25% of the data sample, were combined to determine the TZERO's for the 1994 "+1.5T" data.

### 6.3 Calorimeter

In 1994, 175 calorimeter towers were present. This corresponds to roughly 25% of the full calorimeter. It can measure both the kinetic energy and time, and is a powerful
Figure 6.17: $\beta$ versus H1 slat distribution for all tracks in the $B=+1.5T$ field setting. The neutral line is at slat 35. Positive particles bend toward higher hodoscope slats.

tool in rejecting high mass candidates which are not consistent with strangelets. A portion of the high mass candidates from the tracking mass measurement (using the hodoscopes and straw tubes) strike the calorimeter. These candidates are studied to see whether or not their kinetic energy and time-of-flight are consistent with tracking.

Therefore, the calorimeter needs to be calibrated to measure the kinetic energy and time-of-flight of incident particles.

### 6.3.1 Energy Calibration

This energy calibration was made with the goals of the strangelet search in mind. Because a strangelet will deposit far more energy than ordinary particles, an energy calibration to the 30% level is sufficient. We expect for a strangelet of mass $A$ to be similar to $A$ number of nucleons.

A Cobalt-60 calibration is used to equalize the response of the calorimeter towers, and comparisons between tracked protons and a parameterization of the shower shape from test beam data is used to determine the overall energy scale.

Once the Co-60 gain factor, overall gain factor, and Pedestals are known, kinetic
energy can be determined:

\[
\text{KineticEnergy} = \text{Gain} \times \text{Co - 60Factor} \times (\text{ADC} - \text{Pedestal}) \tag{6.21}
\]

For further details on the energy calibration see Ref. [58].

**Pedestals**

The calorimeter pedestals are sharp and have an RMS of less than 2 ADC channels. No correlation was seen between the calorimeter pedestal and the phase of the 60 Hz clock. The pedestals are determined by finding the peak and doing a 3 channel interpolation around the peak, and are determined for each run.

**Cobalt-60 Calibrations**

A Cobalt-60 source calibration was performed at the end of the 1994 run. This calibration is used to equalize the response of all the calorimeter towers. It should be noted that in order to do this one makes the assumption that the tower response to the Co-60 radiation is the same as the tower response to hadrons. This is not a perfect assumption because the Co-60 radiation deposits most of its energy near the front face of the tower, whereas a hadron shower will penetrate much more deeply into the tower (each tower is about 5.3 interaction lengths). Therefore, the attenuation length variations between fibers will effect the Co-60 radiation differently from hadrons showers. Additionally, only one Co-60 calibration was preformed, and it was done with a lock in amplifier that permitted the integration of only a small amount of charge. Bearing these caveats in mind, and the roughly 20-30% accuracy level desired, this calibration is adequate for the purposes of the strangelet analysis.

**Overall Energy Scale**

Once the pedestal and Co-60 factor are know, the overall gain factor is needed (see Eq. 6.21). This is obtained for the 1994 data by comparing the energy response in the calorimeter of tracked protons, with that from a parameterization of test beam data.
Tracked protons were taken from data at $-0.75 \text{T}$ field setting, where we get a sufficient number of tracked protons to carry out this study. The kinetic energy of the protons is calculated given the known mass of the proton:

$$ KE = \sqrt{p^2 + 0.938^2} - 0.938 \quad (6.22) $$

Proton tracks are then matched to calorimeter peak towers. To be considered a peak tower, it must have more energy than the surrounding eight towers, and must have an energy greater than 0.3 GeV. The proton data sample is then sliced into 1 GeV kinetic energy bins.

In the test beam, hadrons with different kinetic energies were directed at a set of 12 calorimeter towers at various positions. The tower responses were recorded and fit to an overall shower shape. For the purposes of this study, we take the original parameterization [57]. Comparisons between the test beam data and the shower simulation is given in [58]. The simulation is good enough for these purposes, but is not reliable toward the edges of the towers. The parameterization has since been redone, but were not used for this calibration.

The peak tower energy distribution from the data is then compared to that of the simulation. The overall scale factor is found to be $1.1165 \text{ GeV}/(\text{Co-60 count})$.

### 6.3.2 Time Calibration

The timing information from the calorimeter is used to reject clusters which have contamination. First time agreement between tracking and the peak tower is required. Then all nine towers (the peak tower, and the 8 surrounding towers in a $3 \times 3$ grid) must have time agreement. This avoids contamination from late or early hits which are not associated with the particle from tracking. Therefore, a timing calibration on the calorimeter was performed.

The run to run variations in the timing were taken out by a slew time offset method. Because the resolution of the calorimeter is known to be much worse than the hodoscopes (450 ps compared to 120-150 ps) a simpler slew time offset approach is used. After the TDC distributions have been slew corrected, the peak of the TDC
distribution is found. Then a five channel interpolation is carried out. The binning is set at 400 ps per bin. The slew time offsets are determined for each run.
Chapter 7

Analysis

The following four chapters contain the analysis and results of the strangelet search. In this chapter a description of the tracking package and the \( \chi^2 \) and charge cuts which are used for the analysis are presented. At the end of the chapter, mass plots of the full data sample with all the cuts are shown. High mass candidates remain after all the cuts. The following two chapters contain a discussion of the experimental geometric acceptance, high mass candidates, and final results.

7.1 Tracking and Rigidity Reconstruction

A charged particle tracking package is used to find tracks and reconstruct their masses. The quality of the tracking fits is used to select good tracks. The tracking itself is run with “loose” cuts, which yield a single particle tracking efficiency of approximately 98% (see Sec. 8.3). The track quality cuts and charge cuts are applied in a later stage of the analysis (see Secs. 7.2.1 and 7.3).

The tracking package [37] uses the hits in the hodoscopes to define a road that is used to find hits in the other detectors. The H1, H2, and H3 hits are used to project first to the S2 and S3 \( x \)-planes, and then to the S2 \( u \) and \( v \) planes. For the “\( B=+1.5T \)” analysis, the S3 \( u \) and \( v \) planes were not used during tracking. Hits are demanded in all of the detectors (except for S3 \( u \) and \( v \)), or the track candidate is rejected. The downstream \( x \) vs. \( z \) and \( y \) vs. \( z \) track fits are fed into a rigidity
reconstruction program [59] which returns the rigidity \((p/Z)\) and pathlength (from the target to \(z = 10\) m) of the track after M2. The inverse slope of a \(t\) vs \(l\) fit (where \(l\) is pathlength) yields the \(\beta\) of the track using a time point at the target.

The following cuts were used in order to speed up the tracking:

- **\(\beta\) cut.** An estimate of the \(\beta\) of each hit is made by using the average pathlength to each slat. Hits corresponding to \(\beta < 0.985\) \((t < \frac{1}{0.985c} - 2.5\sigma_t)\) are kept.

- **Hodoscope Groups** Only combinations of hits consistent with track candidates that could come from the target are considered. The tracking program starts with H3 hits. It considers only hits in a region (or group) of H2 which could lead to a track which came from the target. Similarly, for each H2-H3 hit pair, only hits in a region of H1 which could lead to a track from the target are considered.

- **\(\delta\theta_x\) and **\(\delta\theta_y\) **cuts.** "Stubs" are formed from valid H1, H2, and H3 hit combinations. Agreement between the slopes formed from H1-H2 and H2-H3 is required:

\[
\delta\theta_x = \left| \frac{x_1 - x_2}{z_1 - z_2} - \frac{x_2 - x_3}{z_2 - z_3} \right| < 0.007
\]

\[
\delta\theta_y = \left| \frac{y_1 - y_2}{z_1 - z_2} - \frac{y_2 - y_3}{z_2 - z_3} \right| < 0.070
\]

Estimates of the effects of these cuts were made by using a Monte Carlo program. The \(x\) slope is dominated by multiple scattering and detector slat size, while the \(y\) slope is dominated by the vertical position resolution. These cuts were chosen to keep more than 99.9% of the data.

With these cuts, the speed of the tracking is limited by tape input/output on a DEC AlphaStation 200-4/233.

Once a track candidate has been found by the three hodoscopes the track is fit via a least squares fit, with the \(x\) and \(z\) positions of the hit scintillator slats being determined by survey. The slope and intercept of the fit are then used to search for hits at S2\(x\) and S3\(x\). The track is projected in the \(x\) direction to S2\(x\) and S3\(x\), and the closest straw cluster within \(\pm 3\sigma\) of the projection error is attached to the
track. If no cluster is found in either S2z or S3z the track is discarded. The track is then refit with the straw tubes, yielding the final downstream horizontal slope and intercept. Similarly, the track is projected in the y direction to the S2 u and v planes. The closest straw tube cluster within ±3σ of the projection error are attached to the track. If no cluster is found in either S2 u or v the track is discarded. The track is then refit using S2 u and v to yield the final downstream vertical slope. Thus, the downstream horizontal slope and intercept is determined from the z vs. z fit, which uses S2z, H1, H2, H3, and S3z, while the vertical slope is determined from the y vs. z fit, which uses S2uv, H1, H2, and H3.

The downstream horizontal and vertical slopes along with the horizontal intercept are used as input to the momentum reconstruction program. The rigidity of the track is reconstructed with the use of a lookup table. Tables were determined by tracking monte carlo particles through magnetic field maps. These maps were obtained using a combination of old measurements, theoretical field shape, and an overall field correction factor. The overall fields in the two magnets were scaled so that the beam deflection through the magnets predicted by the field maps agreed with measured beam deflections during the run. The field maps obtained this way are good to a few percent. The magnets have subsequently been mapped, but these maps were not used in this analysis. In addition to the rigidity of the track, the magnetic field routine returns the pathlength of the track.

7.2 Initial Mass Plots

There were 25,725,467 INT2 triggers from the 1994 "B=+1.5T" running which passed the beam counter cuts. All of these triggers were tracked. The mass distribution with only the loose tracking cuts and rapidity cut is shown in Figs. 7.1 and 7.2. For the analysis, I only keep events in the rapidity range chosen for this analysis (1.1 < y < 2.1), where the rapidity y is determined from the reconstructed momentum along the beam direction (pz) and total energy (E):

\[ y = \frac{1}{2} \log \left( \frac{E + p_z}{E - p_z} \right) \]  

(7.1)
For rapidities greater than 2.1, the mass resolution of the spectrometer deteriorates and we are susceptible to more backgrounds. When the rapidity is smaller than 1.1 there is the danger that the time may not be within our ADC or TDC gates. The \( y \) and \( \beta \) of a particle are related \( \beta = \tanh(y) \). When I refer to the \( \beta \) cut, I am referring to a cut which selects rapidities between 1.1 and 2.1 \((y_{cm} \pm 0.5)\).

Even with the loose tracking cuts, the mass distribution in Fig. 7.1 shows clear peaks. Note that because there is no charge cut, the horizontal axis is mass over charge. The first large peak is thus mostly deuterons, with a small amount of alphas and background. If once considers a region within \( \pm 2.5\sigma \) of the reconstructed deuteron mass, the background is found to be approximately 3.5% of the peak. The second peak is the triton peak. There is approximately 20% background in a region \( \pm 2.5\sigma \) of the triton peak. The shoulder in front of the deuteron peak is the tail of the proton peak. Note that the protons at this field setting have no geometrical acceptance with the rapidity cut that was used. Only the protons which have anomalously slow times due to fluctuations in the hodoscope TDC distribution remain. The biased sample of protons is thus shifted to higher mass than the proton.

Although the mass distribution is fairly clean, we find that 12,843 \( M > 5 \) high mass candidates remain. See Fig. 7.3, which is mass distribution on an expanded scale. Therefore, we wish to make cuts to clean up the data sample, and to resolve the charge of the tracks. In the following sections I describe the charge and \( \chi^2 \) cuts that are applied to the data.

### 7.2.1 Charge Cuts

A charge cut is required to separate tracks with different charges. For the strangelet analysis we are interested in searching for high mass objects with \( Z = 1 \) or 2. The charge 1 cut is also used to eliminate those tracks which deposit only a small amount of energy in a slat, which can come about when a track goes through the edge of the slat, or from a background hit. This "shoulder" on the charge distribution can be seen in Fig. 6.13. The efficiencies of these cuts must be determined.

For the charge 1 cut, we require \( 0.74 < \text{GMADC} < 3.00 \) in all three hodoscopes, where GMADC is the geometric mean of each hodoscope (see Eq. 6.13). The efficiency
Mass Distribution with $\beta$ cut

<table>
<thead>
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<th>ID</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
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</tr>
<tr>
<td>$\chi^2$/ndf</td>
<td>404.1 / 38</td>
</tr>
<tr>
<td>Constant</td>
<td>7482.</td>
</tr>
<tr>
<td>Mean</td>
<td>1.872</td>
</tr>
<tr>
<td>Sigma</td>
<td>0.5885E-01</td>
</tr>
</tbody>
</table>

Figure 7.1: Mass distribution of the full "B=+1.5T" data set. There is a cut requiring $0.802 < \beta < .971$ ($y_{cm} \pm .5$)
Figure 7.2: Mass distribution of the full "B=+1.5T" data set. There is a cut requiring $0.802 < \beta < .971$ ($y_{cm} \pm .5$). Same as Fig. 7.1 but on a log scale.
Figure 7.3: Mass distribution of the full "B=+1.5T" data set. There is a cut requiring $0.802 < \beta < 0.971$ ($y_{cm} \pm 0.5$). Same as Fig. 7.2, but on an expanded horizontal log scale.
Figure 7.4: $Z^2$ in H3 for Charge 1 ($0.74 < \text{GMADC} 1, 2 < 3.0$) and Charge 2 ($3.5 < \text{GMADC} 1, 2 < 9.0$) tracks in H1 and H2.

Table 7.1: Charge cut efficiencies.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Charge 1 ($0.74&lt;\text{GMADC}&lt;3.0$) Cut Efficiency</th>
<th>Charge 2 ($3.5&lt;\text{GMADC}&lt;9.0$) Cut Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
<td>94%</td>
<td>91%</td>
</tr>
<tr>
<td>H2</td>
<td>95%</td>
<td>93%</td>
</tr>
<tr>
<td>H3</td>
<td>96%</td>
<td>92%</td>
</tr>
<tr>
<td>All</td>
<td>85%</td>
<td>77%</td>
</tr>
</tbody>
</table>
of this cut is evaluated separately for each hodoscope. This is done by requiring a
good charge 1 track in two of the hodoscopes, and looking at the charge distribution
of the third hodoscope. The solid histogram in Fig. 7.4 shows the $Z^2$ distribution in
H3 for tracks where $0.74 < GMADC < 3.00$ in H1 and H2. We integrate the area
between the charge cut and divide it by the total number of entries to determine
the charge cut. A similar exercise is performed to determine the H1 and H3 charge
cut efficiencies. Table 7.1 shows the results. Fig. 7.5 shows the mass distribution for
particles with the $\beta$ and $Z = 1$ cuts. It should be noted that there is a $\beta$ dependence
in Eq. 6.11. This leads to a shift of 20% in the mean $dE/dx$ from $y=1.1$ to $y=2.1$.
The effect of this shift on the charge cut efficiency is small (about 0.1%) because the
charge 1 cut is so loose.

For the charge 2 cut, we require $3.0 < GMADC < 9.00$. The efficiency of this cut
is derived in the same way as the charge 1 cut, where we require $4.0 < GMADC < 9.00$
in two hodoscopes. The dashed histogram in Fig. 7.4 shows the $Z^2$ distribution in H3
for tracks where $3.0 < GMADC < 9.00$ in H1 and H2. From this we can determine the
efficiency of charge 2 cut on H3. Table 7.1 shows the results for all three hodoscopes.
Fig. 7.6 show the mass distribution for particles with the $\beta$ and $Z = 2$.

In 1994, charge 3 particles would be out of the range of the ADC's. Overflows
(charge 3 or greater) were not used for this analysis.

7.3 $\chi^2$ Distributions

The $\chi^2$ values from four fits provide information as to the quality of the fit and help
discriminate between real tracks and background tracks. The four fits are $x$ vs. $x$,
$y$ vs. $l$, $y$ vs. $z$, and $t$ vs. $l$, where $l$ is the pathlength of the track from the target.
The $t$ and $y$ fits versus pathlength are the most powerful cuts because they include
the target in the fits.

With the $\chi^2$ cuts we keep 61% of the good deuterons (relative to no $\chi^2$ cuts), while
keeping only 1.2% of the high mass background (see Table 7.5, 7.6). To determine
this efficiency I cut on masses consistent with deuterons, and estimate the background
under the peak. Similarly, as a comparison I cut on masses consistent with tritons, and
Figure 7.5: Mass distribution of the full “B=+1.5T” data set. There is a cut requiring $0.802 < \beta < 0.971$ ($y_{cm} \pm 0.5$) and a charge one cut: $0.74 < \text{GMADC} < 3.0$
Mass Distribution with \( \beta \) and \( Z=2 \) Cuts

![Graph showing mass distribution with peaks at \( ^3\text{He} \) and \( \alpha \) with ID 201 and entries 2110]

Figure 7.6: Mass distribution of the full "B=+1.5T" data set. There is a cut requiring \( 0.802 < \beta < 0.971 \) (\( y_{cm} \pm 0.5 \)) and a charge two cut: \( 3.0 < \text{GMADC} < 8.0 \)
estimate the background under the triton peak. [For the following discussion, when I refer to deuterons, I am referring to the all tracks with a reconstructed mass within $\pm 2.5\sigma$ of the reconstructed deuteron mass. Similarly, tritons refer to all tracks with a reconstructed mass within $\pm 2.5\sigma$ of the reconstructed triton mass. “Good” deuterons or “good” tritons refer to the number of deuterons or tritons after a background subtraction has been performed.] I then look at the mass distributions with the various $\chi^2$, and determine the number of good deuterons after the cut. A comparison before and after the cut yields the percent of good deuterons or tritons remaining after the cut.

We expect the $\chi^2$ distributions of strangelets to look the same as for deuterons, or any other real track. To test whether the mass of the track could affect the $\chi^2$ distribution, deuteron and triton $\chi^2$ distributions were compared, and found to agree well. See Tables 7.5 and 7.6) for a quantitative comparison.

Because there is a correlation between the various $\chi^2$ distributions, the total $\chi^2$ cut efficiency is determined together.

7.3.1 $\chi^2_z$ (x vs. z)

The $\chi^2_z$ refers to the $\chi^2$ value from a fit of x vs. z for the downstream (post M2) measurements. The x fit includes S2x, H1, H2, H3, S3z. The slope in x, and x-intersect at the magnet is used as input to rigidity reconstruction program. The fit has has 3 degrees of freedom.

The $\chi^2_z$ value from the x fit gives information on the quality of the downstream horizontal fit. The x resolutions of the three hodoscopes are taken to be $w/\sqrt{12}$, where $w$ is the width of the slat. The errors associated with a straw tube cluster depends on the number of tubes $n$ in the cluster, and the radius $\tau$ of an individual tube. See Table 7.2 for a summary of errors used for in the fit. Note that the resolution of a straw hit is determined by considering the overlap of the staggered straws. For example, in the case of a cluster size of one, it is localized to one straw diameter, while for a cluster size of two, it is localized to one straw radius. Fig. 7.7 shows the $\chi^2_z$ distribution. The dark solid histogram is filled for all tracks with $\beta < 0.971$ which reconstruct a mass within $\pm 2.5\sigma$ of the mass of the reconstructed deuteron.
Table 7.2: Detector resolutions used for $x$ fit. $w$ is the width of the scintillator slat, $r$ is the radius of a single straw tube, and $n$ is the number of straw tubes in a cluster.

<table>
<thead>
<tr>
<th>Detector</th>
<th>$x$ resolution</th>
<th>$\sigma_x$</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
<td>$w/\sqrt{12}$</td>
<td>.319 cm</td>
</tr>
<tr>
<td>H2</td>
<td>$w/\sqrt{12}$</td>
<td>.435 cm</td>
</tr>
<tr>
<td>H3</td>
<td>$w/\sqrt{12}$</td>
<td>.668 cm</td>
</tr>
<tr>
<td>S2, S3</td>
<td>$r(1+n)/\sqrt{12}$, $n \neq 2$</td>
<td>.058(1+n) cm</td>
</tr>
<tr>
<td></td>
<td>$r/\sqrt{12}$, $n = 2$</td>
<td>.058 cm</td>
</tr>
</tbody>
</table>

Figure 7.7: (a) Comparison between the $\chi^2_x$ distribution expected based on a gaussian position distribution (thin solid line), a flat position distribution (dark dashed line), and deuterons (dark solid line). (b) Comparison between the $\chi^2_x$ distributions for deuterons and $M > 5$ high-mass candidates (dark dashed line). The $\chi^2_x < 2.0$ cut is shown.
No other cuts are applied. Fig. 7.7(a) shows a comparison between the distribution from the data and the expected distribution. Note that the expected distributions are different if one assumes the position distribution across the straws and hodoscopes to be flat rather than gaussian. In our case we expect nearly flat distributions, and this distribution agrees well with the data.

In Fig. 7.7(b) the dark dashed line shows the $\chi^2$ distribution for all tracks with a $M > 5.0$ GeV. Note that there is a scale change between Fig. 7.7 (a) and (b). A clear difference between the deuterons and the high mass candidates is seen. Because we do not expect the $\chi^2$ for strangelets to look similar to that of deuterons or tritons a cut on the $\chi^2$ rejects many more background particles than real particles. Note that all curves are normalized to 1.0 over the range from 0 to 20.

It is illustrative to compare the mass distributions with and without a $\chi^2$ cut. Figs. 7.1 and 7.2 show the mass distribution for particles with $Z = 1$ and $\beta$ between 0.804 and 0.971 (which corresponds to half a unit around central rapidity ($y_{cm} \pm .5$) on a linear and log scale. Fig. 7.13 shows the same distribution with a $\chi^2 < 2.0$ cut. From the plots before and after the $\chi^2$ cut we can estimate at how many good deuterons are eliminated. For the two plots we estimate the number of real deuterons by counting the number of entries between a mass of 1.725 and 2.015, which corresponds to $m \pm 2.5\sigma_m$. We then estimate the background by drawing a straight line from the dip before the deuteron peak to the dip between the deuteron and triton peaks. See Tables 7.5 and 7.6. In addition, we count the number of candidates with $M > 5$ GeV with and without the $\chi^2$ cut. Approximately 89% of the good deuterons are kept, while 74% of mass candidates greater than mass 5 GeV are kept.

7.3.2 $\chi^2_y$ (y vs. z)

The downstream y fit includes S2uv, H1, H2, and H3. The slope in y is fed into the momentum reconstruction. The fit has 2 degrees of freedom.

The hodoscope y resolutions are derived from the time resolutions, while the vertical resolution of the u and v straw chambers depends on the number of clusters. See Table 7.3. The u and v straws are tipped at an angle $\theta \approx 20^\circ$. The straw y
Figure 7.8: $\chi^2_\nu$ distribution comparisons. (a) Comparison between deuterons and the expected $\chi^2$ distribution for two degrees of freedom. (b) Comparison between deuterons and $M > 5$ high-mass candidates. No $\chi^2_\nu$ cut is used in the analysis. The full distributions (which go out to $\chi^2$/DoF=20) are normalized to 1.0.

resolutions are a projection of the straw resolutions onto the vertical axis.

Fig. 7.8 shows the $\chi^2_\nu$ distribution. Fig. 7.8(a) shows a comparison between the distribution from the data and the expected distribution. The dark solid histogram is for deuterons within 2.5$\sigma$ of the deuteron mass. The distributions differ a little near low $\chi^2$ values. This may be indication that the $y$ errors are not quite correct.

In Fig. 7.8(b) the dark dashed line shows the $\chi^2$ distribution for all tracks with a $M > 5.0$ GeV. A clear difference between the deuterons and the high mass candidates can be seen. However, $\chi^2_\nu$ is not used as a cut, because the $\chi^2_{ypl}$ cut (see the next section) is a much more powerful.

7.3.3 $\chi^2_{ypl}$ ($y$ vs. $l$)

The $y$ vs. $l$ (pathlength) fit includes the target, S2uv, H1, H2, and H3. The $\chi^2_{ypl}$ value from the $ypl$ fit gives information on the quality of the vertical fit to the target.

Fig. 7.9 shows the $\chi^2_{ypl}$ distribution. Fig. 7.9(a) shows a comparison between the
Table 7.3: Detector resolutions used for $y$ fit. $w$ is the width of the scintillator slat, $r$ is the radius of a single straw tube, $n$ is the number of straw tubes in a cluster, and $\theta \approx 20^\circ$ is the angle of $u$ and $v$ straws with respect to the vertical.

<table>
<thead>
<tr>
<th>Detector</th>
<th>$y$ resolution</th>
<th>$\sigma_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target</td>
<td>$\frac{w}{n} \sigma_t$</td>
<td>0.2 cm</td>
</tr>
<tr>
<td>H1</td>
<td>$\frac{w}{n} \sigma_t$</td>
<td>2.0 cm</td>
</tr>
<tr>
<td>H2</td>
<td>$\frac{w}{n} \sigma_t$</td>
<td>1.9 cm</td>
</tr>
<tr>
<td>H3</td>
<td>$\frac{w}{n} \sigma_t$</td>
<td>2.4 cm</td>
</tr>
<tr>
<td>S2,S3</td>
<td>$\frac{r(1+n)}{\sqrt{12 \sin(\theta)}}$ $n \neq 2$</td>
<td>$\approx 0.17(1 + n)$ cm</td>
</tr>
<tr>
<td></td>
<td>$\frac{r}{\sqrt{12 \sin(\theta)}}$ $n = 2$</td>
<td>$\approx 0.17$ cm</td>
</tr>
</tbody>
</table>

Figure 7.9: $\chi^2_{y_{pl}}$ distribution comparisons. (a) Comparison between deuterons and the $\chi^2$ distribution for two degrees of freedom. (b) Comparison between deuterons and M > 5 high-mass candidates. The $\chi^2_{y_{pl}} < 1.6$ cut is shown. The full distributions (which go out to $\chi^2$/DoF=20) are normalized to 1.0.
distribution from deuterons (solid line) and the expected distribution (dark dashed line). The expected distribution agrees well with the data.

In Fig. 7.9(a) the dark dashed line shows the $\chi^2$ distribution for all tracks with $M > 5.0$ GeV. A marked difference between the deuterons and the high mass candidates can be seen. The distribution for $M > 5.0$ GeV shows no peak. The difference between the $y$ vs. $z$ and $y$ vs. $l$ fits is the inclusion of the target point. Thus, the difference between the $\chi^2_y$ and $\chi^2_{ypl}$ distributions for high mass candidates imply that they do not come from the target.

Fig. 7.14 show the mass distribution for particles with a $0.804 < \beta < 0.971$, and $\chi^2_{ypl} < 1.6$. Approximately 78% of the good deuterons are kept, while only 11% of candidates greater than mass 5 GeV are kept. See Tables 7.5 and 7.6.

7.3.4 $\chi^2_t$ (t vs. l)
Table 7.4: Detector resolutions used for $t$ fit and derived from time residuals.

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<tr>
<th>Detector</th>
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</tr>
</thead>
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<td>80 ps</td>
</tr>
<tr>
<td>H1</td>
<td>130 ps</td>
</tr>
<tr>
<td>H2</td>
<td>118 ps</td>
</tr>
<tr>
<td>H3</td>
<td>147 ps</td>
</tr>
</tbody>
</table>

The time fit includes target, H1, H2, H3. It has 2 degrees of freedom. This fit gives the $\beta$ of the track.

A time resolution for beam counter and hodoscopes were derived from time residual histograms. A residual histogram for the H2 detector, for example, is derived from making a fit with all the detectors, except for H2. The deviation between the track time at H2, and the H2 time is the residual. Time residual histograms for the target, H1, H2, and H3 are shown in Fig. 7.11. A monte carlo program was written to derive approximate time resolutions from these residuals. As input the program takes the errors for the beam counter, H1, H2, and H3. $t$ and $l$ values are taken for the track is from a typical deuteron track from the monte carlo in "B=+1.5T" running. With no smearing this forms a perfect track. The time distributions for these detectors are then smeared according to a gaussian with the input $\sigma$ values. Using the same procedure as the data, time residuals at the four counters are determined. The $\sigma$s are then varied to reproduce the residuals from the data. Once a new set of time resolutions are obtained, these are used in the data to get a new set residuals from data. This iterative procedure continues until one converges. This procedure converged rapidly. For input time resolutions of 80 ps, 130 ps, 118 ps, and 147 ps for the beam counter, H1, H2, and H3 respectively give time residuals of 335 ps, 146 ps, 150 ps, and 203 ps for the beam counter, H1, H2, and H3. The time residual at the beam counter is so large because it includes a projection error of the downstream hodoscopes. This compares well with the residuals which are 337 ps, 144 ps, 147 ps, and 201 ps from Fig. 7.11. Note that the fits to the data are fits to the gaussian portion of the time residuals.

A confirmation that the time residuals are reasonable is made by comparing the
Figure 7.11: Time residuals at the beam counter, H1, H2, and H3.
Figure 7.12: Mass distribution of the full "B=+1.5T" data set. There is a cut requiring $0.802 < \beta < 0.971 \ (y_{cm} \pm 0.5)$ and a charge one cut: $0.74 < \text{GMADC} < 3.0$
Mass Distribution with $\beta$, $Z=1$, and Chi2x cuts

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<tr>
<td>Constant</td>
<td>5924.</td>
</tr>
<tr>
<td>Mean</td>
<td>1.870</td>
</tr>
<tr>
<td>Sigma</td>
<td>$0.5737E-01$</td>
</tr>
</tbody>
</table>

Figure 7.13: Mass distribution of the full "B=+1.5T" data set. There are cuts requiring $0.802 < \beta < 0.971$ ($y_{cm} \pm 0.5$), $Z=1$ ($0.74 < \text{GMADC} < 3.00$), and $\chi_z^2 < 2.0$. 
Figure 7.14: Mass distribution of the full “B=+1.5T” data set. There are cuts requiring $0.802 < \beta < 0.971$, $y_{cm} \pm 0.5$, $Z = 1$ ($0.74 < GMADC < 3.00$), and $\chi^2_{vpt} < 1.6$. 
Mass Distribution with $\beta$, $Z=1$, and Chi2t cuts

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<tr>
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<tr>
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<tr>
<td>Mean</td>
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<tr>
<td>Sigma</td>
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</table>

Figure 7.15: Mass distribution of the full "B=+1.5T" data set. There are cuts requiring $0.802 < \beta < 0.971$ ($y_{cm} \pm 0.5$), $Z = 1$ ($0.74 < \text{GMADC} < 3.00$), and $\chi^2_t < 1.6$. 
Mass Distribution with $\beta$, $Z=1$, Chi2x, Chi2ypl, and Chi2t cuts

<table>
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<tr>
<td>$\chi^2$/ndf</td>
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</tr>
<tr>
<td>Constant</td>
<td>4188.</td>
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<tr>
<td>Mean</td>
<td>1.870</td>
</tr>
<tr>
<td>Sigma</td>
<td>0.5429E-01</td>
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</table>

Figure 7.16: Mass distribution of the full "B=+1.5T" data set. All the cuts are required: $0.802 < \beta < .971$ ($y_{cm} \pm .5$), $Z = 1$ ($0.74 < GMADC < 3.00$), $\chi^2_x < 2.0$, $\chi^2_{ypl} < 1.6$, $\chi^2_t < 1.6$. 
Figure 7.17: Mass distribution of the full "B=+1.5T" data set. All the cuts are required: \(0.802 < \beta < 0.971\ (y_{cm} \pm 0.5), \ x_z^2 < 2.0, \ x_{ypl}^2 < 1.6, \ x_t^2 < 1.6,\) and \(0.74 < GMADC < 3.00.\) Same as 7.16, but on a linear scale.
\(\chi^2\) distribution from data with that from one expects for a fit with two degrees of freedom. Fig. 7.10 shows the \(\chi^2\) distribution. Fig. 7.10(a) shows a comparison between the distribution from the data and the expected distribution. The expected distribution agrees well with the data. The dark solid histogram is for deuterons with \(\beta < 0.971\).

In Fig. 7.10(a) the dark dashed line shows the \(\chi^2\) distribution for all tracks with \(M > 5.0\) GeV. A large difference between the deuterons and the high mass candidates can be seen. The distribution for \(M > 5.0\) GeV shows no peak. Again, this fit includes the target. It again appears that the background tracks do not come from the target.

Fig. 7.15 show the mass distribution for particles with a \(0.804 < \beta < 0.971\), and \(\chi^2 < 1.8\). We can estimate at how many good deuterons are eliminated. Approximately 83% of the good deuterons are kept, while only 13% of mass candidates greater than mass 5 GeV are kept. See Tables 7.5 and 7.6.

### 7.4 Final Mass Plots

Now that all the cuts have been applied, final mass plots can be made. Figs. 7.16 and 7.17 show charge 1 mass plots for all the 1994 "B=+1.5T" data with all the \(\chi^2\) cuts applied on log and linear scales. Fig. 7.18 shows the \(Z = 1\) mass distribution. There are a total of 66 high mass candidates with \(M > 5\) GeV. The masses, rapidity, transverse momentum, and slat in H3 which high-mass candidate struck can be seen in Table 7.7.

Fig. 7.19 shows the final \(Z = 2\) mass distribution. There is one high-mass candidate around 8 GeV.

Table 7.8 summarizes the total number d, t, \(^3\)He, \(\alpha\) particles and their mass resolutions. These are for the full "+1.5T" data sample when the \(\beta\), \(Z\), and \(\chi^2\) cuts are all applied.
Table 7.5: $\chi^2$ cut efficiencies for particles with $0.802 < \beta < 0.971$ and $Z = 1$. The totals under the deuteron peak represent $\pm 2.5\sigma$ numbers, where $\sigma$ was taken from the fit with no $\chi^2$ cut.

<table>
<thead>
<tr>
<th>Cut</th>
<th>Real Deuterons</th>
<th>Background Under Deuterons</th>
<th>Real Tritons</th>
<th>Background Under Triton</th>
<th>All M&gt;5</th>
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</thead>
<tbody>
<tr>
<td>No $\chi^2$ Cuts</td>
<td>196644</td>
<td>5539</td>
<td>19364</td>
<td>2358</td>
<td>5307</td>
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<tr>
<td>$\chi_x^2 &lt; 2.0$</td>
<td>174679</td>
<td>4104</td>
<td>17013</td>
<td>1353</td>
<td>2517</td>
</tr>
<tr>
<td>$\chi_{vpl}^2 &lt; 1.6$</td>
<td>153614</td>
<td>1511</td>
<td>15387</td>
<td>615</td>
<td>572</td>
</tr>
<tr>
<td>$\chi_t^2 &lt; 1.6$</td>
<td>162750</td>
<td>3420</td>
<td>16123</td>
<td>964</td>
<td>685</td>
</tr>
<tr>
<td>All $\chi^2$ Cuts</td>
<td>119098</td>
<td>827</td>
<td>11908</td>
<td>205</td>
<td>66</td>
</tr>
</tbody>
</table>

Table 7.6: $\chi^2$ and for particles with $0.802 < \beta < 0.971$ and $Z=1$. The totals under the deuteron peak represent the percent of particles kept with the cut compared to no cut.

<table>
<thead>
<tr>
<th>Cut</th>
<th>Real Deuterons</th>
<th>Background Under Deuterons</th>
<th>Real Tritons</th>
<th>Background Under Triton</th>
<th>All M&gt;5</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Cut</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
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<tr>
<td>$\chi_x^2 &lt; 2.0$</td>
<td>89%</td>
<td>74%</td>
<td>88%</td>
<td>53%</td>
<td>47%</td>
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<tr>
<td>$\chi_{vpl}^2 &lt; 1.6$</td>
<td>78%</td>
<td>27%</td>
<td>79%</td>
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<td>$\chi_t^2 &lt; 1.6$</td>
<td>83%</td>
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<td>83%</td>
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<td>All $\chi^2$ Cuts</td>
<td>61%</td>
<td>15%</td>
<td>61%</td>
<td>9%</td>
<td>1%</td>
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Table 7.7: \( Z = 1 \) high mass candidates for the full “+1.5T” data sample when the \( \beta \), \( Z \), and \( \chi^2 \) cuts are all applied.

<table>
<thead>
<tr>
<th>Mass</th>
<th>( p_t )</th>
<th>rap</th>
<th>H3 slat</th>
<th>Mass</th>
<th>( p_t )</th>
<th>rap</th>
<th>H3 slat</th>
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<td>1555.720</td>
<td>690.423</td>
<td>1.971</td>
<td>139</td>
</tr>
</tbody>
</table>
Figure 7.18: High mass candidates. Mass distribution of the full "B=+1.5T" data set. All the cuts are required: $0.802 < \beta < 0.971 (y_{cm} \pm 0.5)$, $\chi^2_2 < 2.0$, $\chi^2_{vpl} < 1.6$, $\chi^2_{t} < 1.6$, and $0.74 < \text{GMADC}_j < 3.00$. 
Figure 7.19: Mass distribution of the full "B=+1.5T" data set. All the cuts are required: $0.802 < \beta < 0.971 \, (y_{cm} \pm 0.5), \chi_x^2 < 2.0, \chi_{iapl}^2 < 1.6, \chi_t^2 < 1.6$, and $0.74 < GMADC_i < 3.00$. Same as 7.16, but on a linear scale.
Table 7.8: Total number and resolutions of d, t, $^3$He, $\alpha$ particles observed the the full "+1.5T" data sample when the $\beta$, Z, and $\chi^2$ cuts are all applied.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Total Number</th>
<th>Mass (GeV)</th>
<th>Sigma (GeV)</th>
<th>$\sigma_m/m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>d</td>
<td>119098</td>
<td>1.87</td>
<td>0.054</td>
<td>2.9%</td>
</tr>
<tr>
<td>t</td>
<td>11908</td>
<td>2.77</td>
<td>0.070</td>
<td>2.5%</td>
</tr>
<tr>
<td>$^3$He</td>
<td>952</td>
<td>2.85</td>
<td>0.099</td>
<td>3.5%</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>234</td>
<td>3.74</td>
<td>0.135</td>
<td>3.6%</td>
</tr>
</tbody>
</table>
Chapter 8

Acceptance and Efficiencies

In this chapter the geometrical acceptance of the detector and tracking and detector efficiencies are studied. Corrections accounting for the acceptance and efficiency will be applied to derive the experiment's sensitivity to strangelet production. The tracking efficiency is broken up into two parts: (1) the single particle tracking efficiency, and (2) the tracking efficiency due to detector occupancy. The Detector efficiencies refer to how efficient a given detector is at recording hits.

8.1 Monte Carlo Programs

Monte Carlo programs were developed to:

1. Calculate the geometric acceptance for different particle species

2. Determine the single particle tracking efficiency

3. Calculate the tracking efficiency due to the occupancy in our detectors

A complete description of the E864 detector is put into GEANT. This description uses the survey data as obtained for the 1994 run. GEANT is used to track particles through the apparatus. The output of the GEANT simulation includes the $x$, $y$, $z$, time of flight, and $\Delta E$ for each particle which deposit energy in a detector, as well as the input kinematic variables for each track which originates at the target. The
output of the GEANT simulation is fed into a program which smears the time of flight and deposited energy to match the resolution of the hodoscope detectors. The data is then output in the same format as raw experimental data. Monte Carlo tracks can be overlayed on experimental data to determine the tracking efficiency due to the occupancies of the detectors.

8.2 Geometric Acceptance Calculations

Because the E864 detector measures only a portion of phase space, the geometrical acceptance of the detector must be understood.

First, in order to get a feeling for the acceptance of the E864 detector at "+1.5T" field setting, charge 1, mass 6 GeV, 12 GeV, and 30 GeV Monte Carlo events were generated with flat rapidity and transverse momentum distributions. Figs. 8.1, 8.2, 8.3 show these acceptances as a function of $y$ and $p_t$.

In order to convert measurements into sensitivities, a production model for the differential cross section must be assumed. As described in Sec. 1.3.3 we take the following form for the differential cross section:

$$\frac{d^2N}{dydp_t} \propto p_t e^{-\frac{2p_t}{<p_t>}} e^{-\frac{(y-y_{cm})^2}{2\sigma_y^2}}$$

(8.1)

where $<p_t>$ is the mean transverse momentum, $y_{cm}$ is the center of mass rapidity, and $\sigma_y$ is the standard deviation of the rapidity distribution of the strangelet. We take $<p_t> = 0.6\sqrt{A}$ and $\sigma_y = 0.5/\sqrt{A}$ (see Sec. 1.3.3). Tables 8.1, 8.2, 8.3, and 8.4 show the acceptances as a function of strangelet mass for $Z=1$ and $Z=2$ with the two different models for $\sigma_y$.

8.3 Single Particle Tracking Efficiency

The single particle tracking efficiency is the efficiency with which the tracking algorithm can reconstruct the hits which originate from a single track which passes through all the detectors. The inefficiency is mainly due to multiple scattering in
Figure 8.1: Acceptance of a charge 1, mass 6 GeV strangelet at the "+1.5T" field setting as a function of rapidity and transverse momentum. The number in each $y$ and $p_t$ bin are in percent. The rapidity range of 1.1 to 2.1 is used in this analysis.
**Z = 1, M = 12** Strangelet Acceptance

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<th>.8</th>
<th>1.2</th>
<th>1.6</th>
<th>2.0</th>
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<th>2.8</th>
<th>3.2</th>
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<td></td>
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<td>6</td>
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<td>6</td>
<td>9</td>
<td>14</td>
<td>30</td>
<td>35</td>
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</tbody>
</table>

Figure 8.2: Acceptance of a charge 1, mass 12 GeV strangelet at the "+1.5T" field setting as a function of rapidity and transverse momentum. The number in each $y$ and $p_t$ bin are in percent. The rapidity range of 1.1 to 2.1 is used in this analysis.
\[ Z = 1, M = 30 \] Strangelet Acceptance

<table>
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<th>Transverse Momentum (GeV/c)</th>
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<th>7</th>
<th>6</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
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<td>14</td>
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<td>6</td>
<td>7</td>
<td>10</td>
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<td>14</td>
</tr>
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</tbody>
</table>

Figure 8.3: Acceptance of a charge 1, mass 30 GeV strangelet at the “+1.5T” field setting as a function of rapidity and transverse momentum. The number in each \( y \) and \( p_t \) bin are in percent. The rapidity range of 1.1 to 2.1 is used in this analysis.
Table 8.1: Acceptance and Tracking Efficiency for Z=1 strangelets generated with $<p_t> = 0.6\sqrt{A}$ and $\sigma_y = 0.5/\sqrt{A}$.

<table>
<thead>
<tr>
<th>Mass (GeV)</th>
<th>Geometric Acceptance 1.1&lt;y&lt;2.1</th>
<th>$\sigma_m/m$</th>
<th>Single Particle Tracking Efficiency</th>
<th>Occupancy Tracking Efficiency 1.1&lt;y&lt;2.1</th>
</tr>
</thead>
<tbody>
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<td>50%</td>
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<td>6</td>
<td>9.9%</td>
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<td>99%</td>
<td>49%</td>
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<td>7</td>
<td>10.9%</td>
<td>2.0%</td>
<td>99%</td>
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<tr>
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<td>2.1%</td>
<td>99%</td>
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<td>47%</td>
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<td>97%</td>
<td>47%</td>
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</table>
Table 8.2: Acceptance and Tracking Efficiency for Z=1 Strangelets generated with $<p_t> = 0.6\sqrt{s}$ and $\sigma_y = 0.5$.

<table>
<thead>
<tr>
<th>Mass (GeV)</th>
<th>Geometric Acceptance 1.1&lt;y&lt;2.1</th>
<th>Single Particle Tracking Efficiency</th>
<th>Occupancy Tracking Efficiency 1.1&lt;y&lt;2.1</th>
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<tr>
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<td>98%</td>
<td>49%</td>
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<td>8.3%</td>
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Table 8.3: Acceptance and Tracking Efficiency for Z=2 strangelets generated with $<p_t>=0.6\sqrt{A}$ and $\sigma_y=0.5/\sqrt{A}$.

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<th>Mass (GeV)</th>
<th>Geometric Acceptance 1.1&lt;y&lt;2.1</th>
<th>$\sigma_{m}/m$</th>
<th>Single Particle Tracking Efficiency</th>
<th>Occupancy Tracking Efficiency 1.1&lt;y&lt;2.1</th>
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</thead>
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<td>97%</td>
<td>48%</td>
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</table>
Table 8.4: Acceptance and Tracking Efficiency for Z=2 strangelets generated with $<p_t> = 0.6\sqrt{A}$ and $\sigma_y = 0.5$.

<table>
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<tr>
<th>Mass (GeV)</th>
<th>Geometric Acceptance 1.1&lt;y&lt;2.1</th>
<th>Single Particle Tracking Efficiency</th>
<th>Occupancy Tracking Efficiency 1.1&lt;y&lt;2.1</th>
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<td>53%</td>
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<tr>
<td>500</td>
<td>3.0%</td>
<td>97%</td>
<td>48%</td>
</tr>
</tbody>
</table>
the apparatus. If the track scatters enough, it can fail the $\delta \theta_x$ cut, $\delta \theta_y$ cut, or may not be able to be reconstructed by the momentum reconstruction program. Monte Carlo simulations are used to evaluate this efficiency. The results are shown in Tables 8.1, 8.2, 8.3, and 8.4. These efficiencies are typically above 98%. Note that losses due to interactions in the apparatus are included in the geometrical acceptance calculations.

8.4 Tracking Efficiency due to Occupancy

The open geometry spectrometer and the design of the E864 vacuum chamber lead to a large number of hits in the detectors which are not associated with tracks coming from the target. Instead, these hits come from the interaction products of particles which hit the vacuum chamber walls, ribs, and flanges. There were a particularly high number of background hits in the first run because the plug described in Chapter 5 was not installed.

If a hodoscope slat which a real track goes through is hit by another particle, the timing and/or pulse-height information will be erroneous. This leads to an inefficiency. Thus, we need to evaluate the tracking efficiency due to occupancy. This was accomplished by overlaying single Monte Carlo tracks upon real data events. The percentage of reconstructed single tracks could then be evaluated. The results are shown in Tables 8.1, 8.2, 8.3, and 8.4. This efficiency is nearly 50%. It is higher in the regions where there is lower occupancy, and lower in regions with high occupancy.

8.5 Detector Efficiencies

The detector efficiencies, which refers to how efficient a given detector is at recording hits, of the straw and hodoscope detectors must be evaluated. The main cause of inefficiency in the straw tube chambers are broken wires, while the largest contribution to the inefficiency in the hodoscopes are tracks which pass in between two scintillator slats.

The detector efficiencies were determined experimentally [37]. The tracking was
Table 8.5: Detector efficiencies averaged over several runs.

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<th>Detector</th>
<th>Efficiency</th>
</tr>
</thead>
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</tr>
<tr>
<td>S2u</td>
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<tr>
<td>S2v</td>
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<td>S3x</td>
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<td>0.97</td>
</tr>
<tr>
<td>H3</td>
<td>0.98</td>
</tr>
<tr>
<td><strong>ALL</strong></td>
<td><strong>0.80</strong></td>
</tr>
</tbody>
</table>

run for several different runs with the absence of the detector whose efficiency we wish to evaluate. For example, to evaluate the efficiency of H1, all of the detectors except H1 were required. We then evaluate the efficiency by looking for a hit which is consistent with the track in the H1 detector. This process is done for H1, H2, H3, S2x, S2u, S2v, and S3x. The results are shown in Table 8.5. The total detector efficiency when we require all the detectors is 80%.
Chapter 9

Character of High Mass Candidates

In this chapter we examine the high mass candidates to determine whether the number and character of the candidates are consistent with the level of background we expect given that the full detector was not installed for the 1994 run. In the last chapter, we found that after all the cuts are applied, we have 66 charge one candidates with $M>5$ and no charge two candidates with $M>10$ remaining.

We first compare the high mass candidates from the data with the expected level of background. We then examine the candidates which strike the portion of the calorimeter which was installed for the 1994 run.

9.1 Background Expected from Proposal

Because the 1994 run did not have the full detector, an important part of the "+1.5T" run was to run enough to see background. During the design of E864 extensive Monte Carlo studies were carried out to determine the sensitivity of the spectrometer. See [18] for details of the simulations. A comparison between the level of the background from the 1994 data and the Monte Carlo from the proposal gives us a gauge to whether we expect the spectrometer reach the sensitivity levels which were derived in the proposal. In this section I report on the background we expect for the
Figure 9.1: Schematic diagram of a neutron interacting in the vacuum window, and sending a very forward proton into the downstream detectors. The track is then reconstructed to have a high mass. Note that the scale is anamorphic.

1994 running conditions based on the proposal Monte Carlo simulations.

In the proposal simulations it was found the we are most susceptible to a background associated with neutron interactions in the upstream vacuum window, the air between the vacuum window and S2, and in the first layer of S2. The neutrons, which do not bend in the magnetic field, can interact downstream of the two magnets, but upstream of the detectors. Some of these interactions can produce a very forward going proton which will be reconstructed to have a high rigidity, and thus appear to be a high mass object.

When reconstructing the mass of a track through a magnetic field, the rigidity is inversely proportional to the angle which describes how much the field bends the track:

$$p/z \propto \frac{1}{\theta} \quad (9.1)$$

The large reconstructed rigidity translates into a large mass:

$$m = \frac{p/z}{\gamma \beta} \quad (9.2)$$

A schematic drawing of this background can be seen in Fig. 9.1.
In order to compare with the 1994 data, the analysis of the Monte Carlo data was run without S1 and scaled to the 1994 conditions. The window and S2 thickness that are used in the experiment are different than those used in the simulation:

- **Window Thickness** In the proposal the window was taken as 0.05 cm of Mylar. In the actual experiment we are using a window composed of 0.0584 cm Kevlar + 0.1272 cm Mylar. The experimental window has an interaction probability 1.938 times larger than that in the simulation.

- **S2 Thickness** In the proposal the S2 straw plane was taken as 0.048 cm Mylar + 2.4 cm Ar. In the experiment, each tube has a 0.00508 cm wall thickness and .4102 cm tube diameter, which translates to 0.061 cm Mylar + 2.46 cm Ar. This represents an experimental interaction probability 1.48 times larger than that used in the simulation.

Table 9.1 summarized the scale factors used to compare the simulation with the data. Here is a summary of the corrections:

- **Number of Simulation Events** In the proposal 125,000 events with interactions in the window and 125,000 events with interactions in S2 were run. For the simulation without S1, we ran 72,500 window interaction events and 72,500 S2 interactions. Thus, when we normalize to the effective number of events, we need to use a scale factor of 0.58.

- **Total Number of Events** Using an adjustment for the differences in the window and S2 thicknesses, and the number of simulation events, the Window interactions represent $4.87 \times 10^6$ events, and the S2 interactions represent $5.85 \times 10^6$ events. These are to be compared with $2.69 \times 10^7$ events from the 1994 data. Thus, scale factors of 5.48 and 4.60 need to be applied to the window and S2 interaction simulations.

- **Tracking and Detector Efficiency** For the simulation, the total efficiency ran between 60% and 70%. For the 1994 data, the efficiency $\epsilon$ is:

$$\epsilon = \epsilon_{sp}\epsilon_{o}\epsilon_{det}\epsilon_{cut} = (0.99)(0.48)(0.80)(.52) = 0.20$$
Table 9.1: Differences between simulation and 1994 Data. For the simulations, 75,500 events with interactions in the window, and 72,500 events with interactions in S2 were generated.

<table>
<thead>
<tr>
<th></th>
<th>Simulation</th>
<th>1994 Data</th>
<th>Scale Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equiv Number Events For Window</td>
<td>$4.87 \times 10^6$</td>
<td>$2.69 \times 10^7$</td>
<td>5.48</td>
</tr>
<tr>
<td>Equiv Number Events For S2</td>
<td>$5.85 \times 10^6$</td>
<td>$2.69 \times 10^7$</td>
<td>4.60</td>
</tr>
<tr>
<td>Tracking and Detector Eff</td>
<td>65%</td>
<td>20%</td>
<td>0.31</td>
</tr>
<tr>
<td>Detector Size</td>
<td>100%</td>
<td>80%</td>
<td>0.80</td>
</tr>
</tbody>
</table>

Table 9.2: Background estimates from simulation.

<table>
<thead>
<tr>
<th>Source</th>
<th>$N(y \pm 0.5)$</th>
<th>Scale Factor</th>
<th>Background Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Window S2</td>
<td>29</td>
<td>1.36</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>1.14</td>
<td>9</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>48</td>
</tr>
</tbody>
</table>
where $\epsilon_{sp}$ is the single particle tracking efficiency, $\epsilon_o$ is the tracking efficiency due to occupancy, $\epsilon_{det}$ is the detector efficiency, and $\epsilon_{cut}$ is the efficiency due to the $\chi^2$ and $Z$ cuts. [See sec 8.3 for the tracking efficiencies and detector efficiencies derived from the 1994 data]. Therefore, there is a scale factor of 0.31 to get from the simulation efficiency to the efficiency for the 1994 run.

- **Detector Size** The simulation included a detector that is larger than the actual detector. The background is spread out evenly through the detector, and therefore, because the actual detector is 80% of the simulation detector, a scale factor of 0.8 is taken.

- **Total Scale Factor** The total scale factors for the window and S2 interaction simulation can now be calculated. For window interactions: scale factor = $(5.48)(0.31)(0.80) = 1.36$. For S2 interactions: scale factor = $(4.60)(0.31)(0.80) = 1.14$.

Table 9.2 shows the predictions from the simulation. The simulation predicts an expected background of 48 high mass candidates, while we see 66 in the 1994 data. We estimate that this prediction is good to a factor of two. Thus, the background level seen in the data is similar to that expected from our proposal. From this, we conclude that the detector system performed as expected, and that we ultimately expect to reach our proposal sensitivity level of $10^{-10}$ per central collision.

### 9.2 Neutrons Interacting in Window

The previous section showed that the observed background from the 1994 data and the expected level of background from our previous simulations are similar. The geometry and analysis used in the old simulation is not exactly the same as the 1994 conditions, so we did a separate study with 1994 geometry and the analysis package used for the 1994 data. A GEANT Monte Carlo program was used to estimate the background from neutron interactions in the vacuum window. Two million neutrons were forced to interact in the window. The hits from the interaction products were then recorded, smeared according to the detector resolutions, and put into the same
Figure 9.2: Reconstructed mass distribution for 2 million neutron interactions in the upstream vacuum window. There are 53 background events with $M > 5$ GeV.

data format as the real data. The events were then reconstructed with the same programs as data events.

The reconstructed mass distribution for 2 million neutron interactions in the upstream vacuum window is shown in Fig. 9.2.

The window is 0.16% of an interaction length, and on the average 9 neutrons hit the window every event (from RQMD, 170 neutrons are produced in central collisions, and 5% of these neutrons hit the window). Therefore, the 2 million neutron interactions correspond to the equivalent of 139 million events.

In addition to a background source from the window, the neutrons can interact in the air between the window and S2, or in the first layer of S2. There is roughly 1 meter of air between the window and S2. This corresponds to 0.19% of an interaction length. The thickness of one layer of S2 corresponds to (0.13%) of an interaction length. Therefore, all three sources correspond to 0.48% of an interaction length, and therefore, the 2 million neutron interactions corresponds to 46 million events. Therefore, this simulation predicts 31 background events for the 1994 data sample.

This is within a factor of two of number of high mass candidates observed. For such
a background estimate, we take this as good agreement.

9.3 Calorimeter Confirmation

The high mass candidates which strike the calorimeter can be examined. If these candidates truly have a high mass, they will deposit an amount of energy consistent with the kinetic energy from the track. If the candidates come from a background such as np scattering (see the next section), we would expect the calorimetric energy to be much lower than the expected kinetic energy of the track.

In order to examine uncontaminated tracks, the following are required:

- Peak tower in fiducial region (at least one tower from edge of calorimeter).
- Agreement between track time and calorimetric time (within ± 2ns).
- Early contamination cut: all nine towers within +2 ns.
- Late contamination cut: all nine towers within −2 ns.

In the full data sample, only 5 high mass candidates pointed to the portion of the calorimeter that was in place during the 1994 run. Of those, only 3 were in the fiducial region. All of the three high-mass candidates pass the cuts listed above.

Fig. 9.3(a) compares the kinetic energy from the track to the energy from the calorimeter. This figure contains all tracks from the full 1994 "+1.5T" data set that pass the tracking cut and the calorimeter contamination requirements. The clump at low mass are tritons which strike the calorimeter. There are so few entries because the deuterons with $\beta < 0.971$ go to the far bend region of the detector at this field setting, while the calorimeter is located toward the neutral line. The energy resolution of the calorimeter is taken to be $\frac{\sigma_E}{E} = \frac{0.55}{\sqrt{E}}$, and the expected energy from the tracking to be $E_{\text{exp}} = 0.95E$ (95% of the energy contained in a nine tower sum). The vertical axis of the figure represents the number of sigmas away the energy deposited in the calorimeter is from the expected energy. The three high mass candidates are not consistent with high mass objects.
Figure 9.3: (a) the number of sigma away from the expected KE of the track vs. mass. The larger dots are candidates with mass from tracking $> 5$ GeV. (b) the mass reconstructed the calorimetric energy and time a downstream H1, H2, H3 time fit. The shaded region are those with mass from tracking $> 5$ GeV.

We can also reconstruct a mass using the energy from the calorimeter, and the timing from the downstream track (using H1, H2, and H3):

$$m = \frac{E_{\text{exp}}}{\gamma - 1}$$  \hspace{1cm} (9.3)

Note that we do not include the target point for the time fit to insure that we are getting the proper timing of the downstream track. The reconstructed mass can be seen in Fig. 9.3(b). The candidates with $M > 5$ are shaded. Within the energy resolution of this method ($\frac{\delta m}{m} \approx 30\%$), these candidates are consistent with protons.

9.4 Conclusions

We conclude that the high mass candidates are consistent with the background predicted from the simulation. In addition, there are no statistically significant peaks in the mass distribution. Therefore, we choose to place limits on strangelet production. Further, the background level seen in the data is similar to that expected from our
proposal. From this, we conclude that the detector system performed as expected and that no unexpected backgrounds were seen. Therefore, if the rest of the apparatus performs to specifications, we ultimately expect to reach our proposal sensitivity level of $10^{-10}$ per central collision.
Chapter 10

Limits on Strange Quark Matter Production

In this chapter, limits on strange quark matter production are presented. The $Z=2$ limits are straightforward, because no candidates with masses above 10 GeV were measured. For the $Z=1$ limits, in which high mass candidates were measured, limits can be set in several different ways: (1) assume no knowledge of background; (2) assume all candidates are background; (3) take your knowledge of the observed background, and perform a background subtraction.

We have chose to set limits by taking the two limiting cases: assuming no knowledge of the background, and assuming that all the candidates are background. The most technically correct method is to perform a background subtraction. However with our limited background statistics this method becomes difficult, although it is still well defined. We choose not to perform the background subtraction method because we believe that we will not obtain a significantly better limit, and because better measurements will be available soon.
Table 10.1: 90% confidence level Poisson upper limits $N_{\text{poi}}$ for $\tilde{N}_B$ observed background events.

<table>
<thead>
<tr>
<th>$\tilde{N}_B$</th>
<th>$N_{\text{poi}}$</th>
<th>$\tilde{N}_B$</th>
<th>$N_{\text{poi}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2.30</td>
<td>5</td>
<td>9.27</td>
</tr>
<tr>
<td>1</td>
<td>3.89</td>
<td>6</td>
<td>10.53</td>
</tr>
<tr>
<td>2</td>
<td>5.32</td>
<td>7</td>
<td>11.77</td>
</tr>
<tr>
<td>3</td>
<td>6.68</td>
<td>8</td>
<td>13.00</td>
</tr>
<tr>
<td>4</td>
<td>7.99</td>
<td>9</td>
<td>14.21</td>
</tr>
</tbody>
</table>

10.1 Determination of Strangelet Limits Assuming No Knowledge of Background

For any strangelet with mass $m$ in our range we can calculate the mean number of $\tilde{N}_B(m)$ of background events which we will observe within $2.5\sigma$ of the mass resolution at mass $m$:

$$\tilde{N}_B(m) = \sum_{m-1.25\sigma}^{m+1.25\sigma} N_{\text{cand}}(m)$$ (10.1)

$N_{\text{cand}}(m)$ is the number of observed high mass candidates the $2.5\sigma$ interval centered on $m$. The mass resolution $\sigma$ as a function of mass can be read off from Tables 8.1, 8.3. [The minimum resolution was taken as 3%, which was what was measured. The difference between 3% and the best Monte Carlo mass resolutions is attributed to the fact that only an approximation was made for the field shapes.] We choose to set limits in a mass range between 10 GeV and 200 GeV. We do not fit to lower masses because in the first run we will not have competitive limits compared to previous experiments below $m = 10$ GeV. In this mass range, there are 25 charge 1 background events.

We then ask from Poisson statistics what number of events $N_{\text{poi}}(n)$ are such that there is a $\leq 10\%$ chance that $N_{\text{poi}}(n)$ or more events occur due to the given background level of $\tilde{N}_B(m)$ observed events. Note that there are no charge 2 candidates with mass greater than 10 GeV. Therefore, $N_{\text{poi}} = 2.30$ for all masses for charge 2.

The 90% confidence level limits for the production of strange quark matter can
then be calculated:

$$90\% \text{ cl Limit} = \frac{N_{\text{pot}}(\bar{N}_B)}{\text{acc}(m) \times \epsilon(m) \times N_{\text{evt}} \times \text{norm}}$$ (10.2)

$N_{\text{pot}}(\bar{N}_B)$ is the 90% confidence level from Poisson statistics given a background of $\bar{N}_B$ events. $\text{acc}(m)$, which is the acceptance of a strangelet at a given mass, is given in Tables 8.1, 8.2, 8.3, and 8.4.

$$\epsilon(m) = \epsilon_{sp}\epsilon_o\epsilon_{det}\epsilon_{cut},$$ (10.3)

$\epsilon_{sp}(m)$, which is the single particle tracking efficiency, ranges from 97% to 99% (see the tables in chapter 8); $\epsilon_o(m)$, which is the tracking efficiency due to occupancy, ranges from 45% to 60% (see the tables in chapter 8); $\epsilon_{det} = 0.8$ is the detector efficiency (see Sec. 8.5); $\epsilon_{cut}$, which is 0.61$\times$0.85 for $Z = 1$ and 0.61$\times$0.71 for $Z = 2$, is the efficiency due to the $\chi^2$ and $Z$ cuts (see Table. 7.1 and 7.6); $N_{\text{evt}} \approx 25.7 \times 10^6$ is the total number of central events analyzed; norm $= 0.79$ is a correction because we are only counting strangelets within $\pm 1.25$ sigma.

Figs. 10.1 and 10.2 show the 90% confidence level limits for charge 1 and charge 2 strange quark matter production. E864 selects on the 10% most central triggers (those with the lowest impact parameters). So our measured limit corresponds to the lines labelled "10% most central interactions." Included on the charge 2 plot are the results from experiment E878 [31]. [For a charge 1 comparison between E864 and E878 see Sec. 10.3.] In order to compare with these limits, we need to make an assumption about the fraction of strangelets that would be produced in the 10% most central collisions. The lower line corresponds to the limit if all strangelets were produced in the 10% most central collisions.

We can get a rough gauge on the percentage of strangelets produced in the 10% most central collisions by looking at the calculations made by Baltz et al.,[21], which examines strange cluster formation in heavy ion collisions. For the $^6_{\Lambda\Lambda}$He, which is the heaviest system they consider, they predict the minbias and central production (where they define central as the 4% most central collisions). If we take a flat production over the range of 4% most central to 10% most central, they predict that 50% of the $^6_{\Lambda\Lambda}$He are made in the 10% most central collisions. Therefore, an estimate based on
Figure 10.1: 90% confidence level limits for charge 1 strange quark matter production. This limits are set assuming no knowledge of the background.
Figure 10.2: 90% confidence level limits for charge 2 strange quark matter production. A comparison is made with experiment E878.
this prediction would be that 50% of all strangelets are produced in the 10% most central collision.

The E864 limits do not vary much for the two different production models (Eq. 1.7), and the limits are fairly constant as a function of mass. Both models take \( \langle p_t \rangle = 0.6\sqrt{A} \). Two forms are taken for \( \sigma_v \): \( \sigma_v = 0.5 \), and \( \sigma_v = 0.5/\sqrt{A} \). E878 (or any focusing spectrometer) becomes sensitive to the choice of the rapidity distribution because they measure toward the edge of the rapidity distribution for rigidities above their highest rigidity setting. Therefore, they rapidly become less sensitive for narrower rapidity distributions. In contrast, E864 measures around center of mass rapidity. Therefore, the measurements are not very sensitive to the rapidity distribution. Because E864 measures within \( \pm 0.5 \) units of center of mass rapidity, E864 actually becomes slightly more sensitive for narrower rapidity distributions.

10.2 Expected shape of np Scattering Background

In order to set limits of strangelet production as a function of mass while assuming all the candidates are background, a shape for the np scattering background must be assumed. In this section, I sketch the derivation of a simple analytical expression for the shape of the np background. See [60] for the full derivation.

Because \( m = \frac{p}{\gamma} \),

\[
\frac{dN}{dm} = \frac{1}{\beta \gamma} \frac{dN}{dp} = \frac{1}{\beta \gamma} \frac{dN}{d\theta} \frac{1}{dp}
\]  

(10.4)

\( \frac{dN}{dp} \) is derived by simplifying the two magnet system into a single magnet with a larger bending power. The momentum can then be determined analytically with a single bend approximation:

\[ p \propto \frac{1}{\beta} \]  

(10.5)

From this, \( \frac{dN}{dp} \) can be calculated.

\( \frac{dN}{d\theta} \) is derived by considering the geometry of the detectors and the allowable vertical deviations. The scattering is isotropic, but the amount of phase space which is allowable is limited when imposing a vertical angle cut, which is determined by the
Figure 10.3: Reconstructed mass distribution for 2 million neutron interactions in the upstream vacuum window with only a $\beta$ cut. The fit is to the expected background function, and the distribution is normalized so that the integral between 10 and 200 is 25 which is the number of high mass candidates in the actual data sample.

vertical resolution of the H3 detector. It is found that:

$$\frac{dN}{d\theta} \propto \frac{1/\theta_y^{max}}{1 + (\theta/\theta_y^{max})}$$  \hspace{1cm} (10.6)

where $\theta_y^{max}$ is the largest vertical scattering allowable due to the vertical resolution of H3.

An expression for the shape $f(m)$ can now be written down:

$$f(m) = \frac{dN}{dm} \propto \frac{1}{m^2 + \alpha^2}$$  \hspace{1cm} (10.7)

The constant $\alpha$ is determined by fitting to the data from the Monte Carlo that was used to estimate the background from np scattering in the previous chapter. This fit is shown in Fig. 10.3 By looking at Fig. 10.3 we can see that this analytical expression fits the background from the Monte Carlo well. In this fit, $\alpha = 12.4$. 
10.3 Dermination of Strangelet Limits Using an Assumed Background Shape

In order to set a limit which is smooth versus mass, we take all the high mass candidates to be background. The predicted shape of the background is normalized to the number of background events measured between 10 GeV and 200 GeV. We do not fit to lower masses because in the first run we will not have competitive limits compared to previous experiments below $m = 10$ GeV. In this mass range, there are 25 charge 1 background events, and thus, we normalize $f(m)$ such that

$$\int_{m=10\text{GeV}}^{m=200\text{GeV}} f(m) dm = 25$$  \hspace{1cm} (10.8)

For any strangelet with mass $m$ in our range we can calculate the mean number of $\bar{N}_B(m)$ of background events which we will observe within $2.5\sigma$ of the mass resolution at mass $m$:

$$\bar{N}_B(m) = \int_{m-1.25\sigma}^{m+1.25\sigma} f(m) dm$$  \hspace{1cm} (10.9)

The mass resolution as a function of mass can be read off from Tables 8.1, 8.3. [The minimum resolution was taken as 3%, which was what was measured. The difference is attributed to the fact that only an approximation was made for the field shapes.]

We then ask from Poisson statistics what number of events $N_{\text{poi}}(n)$ are such that there is a $\leq 10\%$ chance that $N_{\text{poi}}(n)$ or more events occur given a background level of $\bar{N}_B(m)$ observed events. Note that there are no charge 2 candidates with mass greater than 10 GeV. Therefore, $N_{\text{poi}} = 2.30$ for all masses for charge 2.

Included on the charge 1 plot are the results from experiment E878[31].
Figure 10.4: 90% confidence level limits for charge 1 strange quark matter production. The limits are set assuming that all candidates are background. A comparison is made with experiment E878.
Chapter 11

Conclusions

11.1 Detector Performance

In this thesis I presented the results of the "B=+1.5T" data from the first (fall 1994) run of the E864 spectrometer. The detector performed as expected from the E864 proposal, and the number and nature of high mass candidates was consistent with that from background calculations used for the proposal. In simulations it was found that the addition of S1 gives us an added sensitivity of 100, while data from a test beam showed that calorimeter gives us an added sensitivity of 20,000. From this we conclude that if the rest of the apparatus performs as expected, E864 should be able to reach its ultimate sensitivity levels when the full apparatus is in place.

11.2 Interpretation of Strangelet Limits

The 1994 E864 strangelet limits place a significant limit on the existence of high mass strangelets. A high mass strangelet would most likely be produced via a QGP and, therefore, the results can be interpreted to put a limit on the combination of two processes: (1) Central Interaction $\rightarrow$ QGP; (2) QGP $\rightarrow$ Strangelet. Fig. 11.1 shows the constraint of the combination of QGP $\rightarrow$ strangelet and 10% central Au+Pb $\rightarrow$ QGP for $M = 15$ GeV. Reference [24] predicts that a QGP may be nucleated from hadronic matter as often as 1/100 or 1/1000 central collisions. If we assume that a
Figure 11.1: Constraint of the combination of QGP → strangelet and 10% central Au+Pb → QGP for Z=1 and Z=2. M = 15 GeV strangelets.

QGP is formed once every 500 collisions, then the BR(QGP→Strangelet) < 0.029 for charge 1 M = 15 GeV strangelets, and BR(QGP→Strangelet) < 0.0015 for charge 2 M = 15 GeV strangelets, where BR refers to the branching ratio. Because the E864 limits are fairly flat with mass it is similar for other masses.

Note that in the branching ratios above, strangelets are required to have a lifetime long enough to make it through our entire apparatus. Strangelets produced at center-of-mass rapidity would need to live 40 ns in their frame to be detected in the E864 calorimeter.

These upper limits are not sensitive enough to test the coalescence production level of strangelets.

11.3 Prospects for the Future

This thesis represents the first strangelet search from the E864 detector. In coming years, the detector should be able to detect strangelets down to a sensitivity level of $10^{-10}$ per central collision. This should allow E864 to continue to address high
mass strangelets at a higher sensitivity level. In addition, these sensitivity levels will begin to address strangelet production through the process of coalescence for low mass strangelets. It should take approximately two years (where a year includes one AGS 8 week run) of good running to achieve our final sensitivity limits.

Strangelets are predicted to become more stable as they become more massive. Therefore, it is likely that even if stable strangelets exist, they have masses larger than can be produced via the coalescence mechanism. However, if these strangelets do exist, it is possible that metastable strangelets with lifetimes similar to hyperons might exist. Therefore, work has begun to upgrade the E864 detector to be sensitive to strangelets with hyperonic lifetimes.
Appendix A

Survey Sheets from F13 to the E864 Target
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Filename: SYGA
Initial Coordinates: N 9810.2400 E 11516.8490

10-Mar-94
## A-LINE SWITCH YARD

Experiment No.  
By J. SHOMER

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Bibliography


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[55] N.George, Transparancies from group meeting (March 31, 1995).


[57] This parameterization was performed by R.Cernai and C.Pruneau.

