FORWARD BARYON DISTRIBUTIONS IN RELATIVISTIC HEAVY ION COLLISIONS

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A study of the distributions of protons and neutrons emitted into the forward
direction in relativistic heavy ion collisions has been conducted in order to
characterize the processes inherent in collisions of 14.6 GeV per nucleon $^{28}$Si
incident on $^{208}$Pb, $^{64}$Cu, and $^{27}$Al targets. Two components of the nucleon rapidity
and transverse momentum spectra are apparent, corresponding to nucleons that
have interacted with the target nucleus during the collision and those that have not
been involved in an interaction. The number of non-interacting nucleons has been
measured as a function of the collision impact parameter. For the smallest impact
parameters, this number is used to extract an in-medium interaction cross section
for all three targets that agrees with the free nucleon-nucleon cross section at the
collision energy.

The transverse momentum and rapidity distributions of both components of
the nucleon spectra are measured. The transverse momentum spectra are fit to a
thermalized Boltzmann distribution with temperatures approaching 200 MeV at a
rapidity of 2.6. This along with the low number of non-interacting nucleons at small
impact parameters implies that a volume of very hot and dense matter is being
formed in heavy ion collisions at these energies, indicating that conditions are favorable for the formation of a quark-gluon plasma, even though all of the nucleon data are well reproduced by models that do not assume the presence of a plasma. If a quark-gluon plasma is being formed in these collisions, it is not occurring very often.

The nucleon measurements are made using the Brookhaven National Laboratory Alternating Gradient Synchrotron experiment E814, which consists of four-pi calorimetry for event characterization and a magnetic spectrometer located in the forward direction. The apparatus and technique used to identify and characterize the nucleons is described.
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To my Mother and Father
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**LIST OF ABBREVIATIONS**

1. QGP  Quark-gluon plasma  
2. QCD  Quantum Chromodynamics  
3. AGS  Alternating Gradient Synchrotron  
4. SPS  Super Proton Synchrotron  
5. RHIC  Relativistic Heavy Ion Collider  
6. GeV/A  GeV per nucleon  
7. BSCI  Beam Scintillators  
8. TCAL  Target Calorimeter  
9. MULT  Silicon Multiplicity Detector  
10. PCAL  Participant Calorimeter  
11. TPAD  Target Paddles  
12. DC  Drift Chamber  
13. FSCI  Forward Scintillators  
14. UCAL  Uranium Calorimeters  
15. CPU  Central Processing Unit  
16. ADC  Analog to Digital Converter  
17. TDC  Time to Digital Converter  
18. FERA  Fast Encoding Readout ADC
CHAPTER 1: INTRODUCTION

The topic of this dissertation is the distributions of forward nucleons in relativistic heavy ion collisions. This dissertation is concerned with studying the physics processes involved when heavy ions traveling at relativistic velocities collide with other heavy ions at rest in the laboratory. This study is accomplished by measuring the distributions, after the collision, of the protons and neutrons originally present in the projectile nucleus. From these distributions, it will be demonstrated that hot and dense nuclear matter can be created in the laboratory. Described in this introductory chapter is an overview of the new, exciting, and growing field of relativistic heavy ion physics, which should familiarize the reader with the goals, experimental techniques, and terminology of the field. The introduction will also describe the observables measured for the forward nucleons along with what can be learned from the measurements about the dynamics of the nuclear system during the collision.

1.1: RELATIVISTIC HEAVY ION PHYSICS

The primary goal of the new field of relativistic heavy ion physics is to search for a unique form of matter called the quark-gluon plasma, also abbreviated as QGP. The challenges that must be met in this field are to understand the dynamics of relativistic heavy ion collisions, discover a manner in which to detect the quark-gluon plasma (if it is being produced), and then to measure the properties of the plasma. This job is not as straightforward as it sounds because of the high energy of the collisions being studied. The individual nucleon-nucleon collisions occur above the production energy threshold of many particles, most
abundantly kaons and pions. It is necessary for any measurement to be able to
distinguish experimental signals originating from the quark-gluon plasma and signals
present from common hadronic physics processes, which means that it is imperative
that the relativistic heavy ion physicist thoroughly understand the known physics at
the energies involved. In addition, there are also collective effects contributed by
the nuclei themselves that must be identified and understood. The field of
relativistic heavy ion physics also studies hot and dense matter physics, which is
exciting since these studies probe various stages in the evolution of the early
universe.

Why is there so much excitement about finding the quark-gluon plasma? This
question can be answered by understanding what the QGP is. Normal matter
( the matter most people deal with in their everyday lives ) is made up of nuclei
consisting of protons and neutrons, or nucleons. The nucleons, as with all baryons,
consist of three quarks assigned quantum numbers called flavor, such as up and
down. For example, the proton contains two up quarks and a down quark while the
neutron has two down quarks and an up quark. There are also particles named
mesons that contain two quarks - a quark and an antiquark. An isolated quark has
never been detected. All quarks have always been found bound together as baryons
or mesons, collectively called hadrons. It is hypothesized that particles called gluons
transmit the strong force that holds the hadrons together. Isolated quarks have not
been found since the strong force becomes stronger with increasing distance
between the quarks, so it becomes impossible to provide enough energy to separate
the quarks from each other. This phenomenon can be contrasted with a more
familiar force such as the gravitational force, which decreases in intensity as the
square of the distance between the two objects. The existence of a QGP would
allow quarks to exist in a state other than a meson or baryon bound state, since it is
a plasma of free quarks and gluons. Inside the QGP, hadrons lose their identity -
the "bags" containing the quarks within the hadron effectively disintegrate - and the quarks and gluons are able to move freely within the volume of the plasma.

A fundamental theory describing strong interactions is Quantum Chromodynamics, or QCD. QCD has been applied to study interactions between nuclei at very high energies using lattice Monte Carlo techniques. These simulations predict that nuclear matter should undergo a phase transition to a quark-gluon plasma if the temperature of the system is sufficiently high, or if the matter is sufficiently dense. A schematic diagram of nuclear matter based on these calculations is shown in Figure 1.1, which plots the density of the nuclear medium in units of the density of normal nuclear matter versus the temperature of the system. Above and to the right of the two thin curves is the region where QCD calculations predict the formation of the quark-gluon plasma. The region between the thin-lined curves denotes the area of a mixed phase of plasma and hadron gas. Below this region lies the hadron gas. Normal nuclear matter is marked by the semicircle at the bottom of the plot. A transition to a QGP can occur if, for low baryon density, the system is heated above about 200 MeV, or if for low temperature, the system is compressed to about six times that of normal nuclear matter, which has a baryon density of 0.16 nucleons / fm³. Also shown in Figure 1.1 are three trajectories, or paths, followed by specific processes, indicated by the thick lines. The first relativistic heavy ion measurements were made by the Lawrence Berkeley Laboratory Bevelac which accelerates ions to an energy of 1-2 GeV per nucleon. (also written as GeV/A). The phase diagram trajectory followed in collisions at this energy is not expected to cross over into the QGP region, and measurements have thus far confirmed this assumption. Soon after the Big Bang, the universe is predicted to have existed in a QGP state. The trajectory followed by the early universe started in the QGP region and moved into the hadronic region at a time of about one second after the Big Bang. Investigations of the QGP could give us
Figure 1.1: Proposed phase diagram of nuclear matter.
information about the state of the early universe. The trajectory followed by heavy ion collisions at 10-20 GeV/A, where the Brookhaven Alternating Gradient Synchroton operates, could have a chance to enter the QGP region as shown in Figure 1.1, which is the phase trajectory that is investigated in this dissertation. A primary concern of the analysis presented here is to determine the extent of the heating and compression occurring in collisions at energies in the 10-20 GeV/A range. Currently under construction at BNL is the Relativistic Heavy Ion Collider, or RHIC, which will collide Au ion beams with an energy of 100 GeV/A, easily creating conditions where the QGP is expected to be formed.

The process by which QCD predicts the formation of the QGP is simply explained by S. Nagamiya.6 As the temperature increases in the collision system, quarks and antiquarks are created in a manner such that the distance between quarks becomes smaller than what is seen in a hadronic system, which is about 1 fermi. With the smaller distance between quarks, the interactions between the quarks become very small due to the linear dependence of the strong force on the quark separation. As a result, each quark behaves like a free particle in the plasma volume due to the relative weakness of the strong interactions. This explanation holds also for a system which is compressed, since the quarks are basically pushed into each other, also reducing the distance between the quarks and making it possible for a QGP to form.

The primary challenge facing the field of relativistic heavy ion physics is being able to detect the quark-gluon plasma if it is formed in a nuclear collision. The QGP will be impossible to detect directly using current technology since it is confined to a volume extended over a few cubic fermis and will last only about $10^{-23}$ seconds. With today's technology, no detector can presently measure distance and time scales of these magnitudes. Therefore, it is necessary to look for indirect methods to ascertain the presence of the QGP by looking for it in the residues of the
collision. A review of the present experimental techniques being attempted can be found in the proceedings of the Quark Matter '88 conference. The following discussion will summarize some of the proposed QGP signatures and will explain the current experimental status of each signature.

One method of examining what may be happening in heavy ion collisions is to measure particles that are not present in the initial target and projectile nuclei. For example, the initial system consists only of nucleons containing up and down quarks. What can be learned by measuring particles containing strange quarks, which must be produced in quark-antiquark pairs during the collision? When a strange quark and an anti-strange quark are produced in a QGP, the anti-strange quark has a high probability to bind with the originally present up quarks to form a positively charged kaon, $K^+$. On the other hand, the strange quarks have a much lower probability to bind with anti-up quarks, which must also be produced during the collision, to form a negatively charged kaon, $K^-$. Meanwhile, pions ($\pi^+, \pi^-$) are being produced in pairs in equal amounts during the collision. In order to compare the production rate of $K^+$ to $K^-$, the ratio of $K^+$ to $\pi^+$ particles and the ratio of $K^-$ to $\pi^-$ particles can be measured and compared to these same values produced in non-nuclear proton-proton collisions. An increase in the $K^+ / \pi^+$ yield with no increase in the $K^- / \pi^-$ yield when comparing A-A collisions to p-p collisions could be an indication of the existence of the QGP. This yield has been measured in the AGS experiment E802, giving the ratios $K^+ / \pi^+ = 19.2 (3) \%$ and $K^- / \pi^- = 3.6 (0.8)\%$. Proton-proton interactions yield $K^+ / \pi^+ = 4.8 \%$ while $K^- / \pi^- = 2.4 (2) \%$.

Strange particle production has also been studied at the CERN Super Proton Synchrotron (SPS), which accelerates heavy ions to energies of 60 GeV/A and 200 GeV/A. The strangeness enhancement seems to be present in CERN measurements also, but it is not clear if the enhancement is due to the above
mechanism, or if it is due to another process such as suppression of the $\pi^+$ particles or the effects of rescattering in hadronic processes.

Measurements also focus on another flavor of quark, the charm quark, by measuring the $J/\psi$ particle, which is a bound state of a charm quark and an anti-charm quark. In a quark-gluon plasma, there will be many different quarks located very close to each other. In this situation, Debye screening of the color charge can prevent the combination of the charm quark-antiquark pair. If this occurs, $J/\psi$ production will be effectively suppressed in the high quark density environment of the QGP. This effect is investigated by comparing the $J/\psi$ yield from peripheral collisions, where the QGP is not likely to be formed, to the $J/\psi$ yield from central collisions. The NA38 experiment at the CERN SPS has performed this analysis finding about a 40% reduction of the $J/\psi$ yield relative to the continuum when going from peripheral collisions to central collisions. But again, this process can also be explained as being a result of known hadronic processes. The $J/\psi$ particle could interact with the other mesons and nucleons present, accounting for the observed suppression.

Another signature of the QGP could be provided by photons produced in the plasma itself. Once a photon is produced within the plasma, there is little chance that it will interact on its way out of the reaction volume. This fact makes the photon ( and also any produced lepton and muon pairs ) excellent probes of the entire plasma volume by examining, for example, the shape of the photon transverse momentum distribution. Determining whether or not the photons are produced by the plasma is difficult but straightforward by comparing the measured yield to the expected photon yield due to hadronic processes alone. Photon measurements have been attempted by the HELIOS and WA80 collaboration at the CERN SPS. The total transverse momentum spectra of all resultant photons are measured and
compared to the spectra expected from purely hadronic processes. Neither of these experiments see strong evidence for photons originating from a plasma.

It is clear that no irrefutable proof of the existence of a quark-gluon plasma has been found to date, even though the data is apparently suggestive. There is a need for a better understanding of the dynamics of relativistic heavy ion collisions. This dissertation will take an approach differing from those described above by studying whether the environment created in relativistic heavy ion collisions is conducive to the formation of a plasma.

1.2: COLLISION GEOMETRY AND DYNAMICS

In this section, definitions of some of the terms necessary to describe the geometry and dynamics of a relativistic heavy ion collision will be presented. Figure 1.2 shows a schematic of the collision in the center of mass frame before (the top two figures) and after the collision (the bottom two figures). Before the collision, the projectile and target nuclei approach each other head-on, as depicted in the upper sketches. The transverse distance from the center of the projectile to the center of the target is called the impact parameter, labelled b. If the impact parameter is large, resulting in no or very little overlap between the volumes of the two nuclei, the collision is termed a peripheral collision, illustrated in the upper right. If the impact parameter is small, up to full overlap of the two nuclei, the collision is termed a central collision, as illustrated in the upper left.

During the collision, portions of the colliding nuclei will intersect each other and interact. The nucleons in the regions involved in the geometrical intersection are termed the participant nucleons. The nucleons outside of this region, which are essentially sheared off of the original nucleus and continue in their original
direction, are termed *spectator nucleons*. During the collision, the participant nucleons collide or interact, to the extent that a region of hot and dense matter (or maybe even a quark-gluon plasma) is created, where there is enough available energy to produce many pions, kaons, and other particles. One of the concerns of his dissertation is to determine how hot and dense the participant region is at the AGS energies of 14.6 GeV/A, where it is expected that the two nuclei will collide in their overlap volume, and that the participant nucleons will completely stop. At higher energies such as at the CERN SPS or RHIC, it is expected that the two nuclei will pass through each other creating a baryon free region in the volume between the departing nuclei, and this could include the QGP. After the collision, this region quickly expands and cools and the produced pions, kaons, and other particles escape the collision region. The spectator nucleons continue in their original direction, usually fragmenting into smaller nuclei or individual nucleons.

There are a few hundred particles produced during a typical relativistic heavy ion collision at AGS or CERN energies. Ideally, an experiment would strive to completely identify and characterize every particle emitted from the collision. Figure 1.3 illustrates the practical problems with this strategy by showing data obtained from one event in the NA35 streamer chambers in a 200 GeV/A $^{32}$S + Au collision at the CERN SPS. This single event contains roughly 600 charged particles. About half this number of charged particles are emitted after a heavy ion collision at AGS energies. Only at great monetary and personnel expense would it be possible to fully track each particle resulting from these collisions, so experiments attempt to find other methods to be able to fully understand and characterize an event without tracking all of the particles. The quark-gluon plasma is expected to be produced more favorably in the most central collisions. Therefore, an experiment searching for a QGP must have a method by which to determine the impact parameter of the collision. This must be done for two reasons. The first is to define
INTRODUCTION: COLLISION GEOMETRY AND DYNAMICS

Before the Collision:

Peripheral Collision

Center-of-mass frame

After the Collision: \((SI + Al)\)
AGS Energies (14.6 GeV/A)

Participant (QGP)?

Spectator

Central Collision

After the Collision: \((A + A)\)
(Higher Energies)

Quark-Gluon Plasma?

Figure 1.2: Relativistic heavy ion collision geometry.
Figure 1.3: Streamer chamber event recorded by the CERN experiment NA35 with a 200 GeV/A $^{16}$O + Pb collision. There are more than 600 recorded charged particles in this event. The beam enters the figure from the left.
a minimum impact parameter required for the experiment to analyze an event, otherwise too many uninteresting events would be recorded. The second reason is that it is very instructive to measure observables as a function of impact parameter. Before the collision, there are no particles traveling in a direction transverse to the propagation of the beam aside from the fermi motion of the nucleons within the colliding nuclei. In a peripheral collision, there are very few interactions due to the small overlap region of the two incident nuclei, and most of the particles will continue to travel in the longitudinal direction. In a more central collision, many interactions will occur and many of the particles will be scattered or will be emitted transversely. A more central collision will yield more particles in the transverse direction, thus providing a means by which to measure the impact parameter. This transverse particle yield is measured experimentally from the energy deposited in the region transverse to the direction of the projectile or from the multiplicity, or number, of charged particles, $N_c$, produced. The transverse energy is defined as $E_t = E \sin (\Theta)$, where $\Theta$ is the angle of the particle in spherical coordinates with respect to the beam direction. There is no attempt to identify the particles while obtaining an $E_t$ or $N_c$ measurement due to the large number of particles involved. However, most of these particles are pions. More details on this type of measurement will be given in the next chapter.

There are several observables that are useful for describing relativistic heavy ion collisions, and these will be used throughout this dissertation. Experiments in this field are generally concerned with measuring the resultants of the collision in two directions: longitudinal and transverse. The first of these is the longitudinal direction, which is described by the variable referred to as the rapidity, or $y$, which is the Lorentz invariant longitudinal velocity of the particle. Rapidity is a useful variable in relativistic situations since it is additive under Lorentz transformations.
The rapidity is defined as \[ y = \frac{1}{2} \ln \left( \frac{E + p_\parallel}{E - p_\parallel} \right) = \tanh^{-1} \left( \frac{p_\parallel}{E} \right), \] where \( E \) is the energy of the particle and \( p_\parallel \) is its longitudinal momentum. At AGS energies, or a Si beam energy of 14.6 GeV per nucleon, the projectile nucleons have a rapidity of 3.44 and the target nucleons have a rapidity of zero. Other relativistic variables can be expressed in terms of the rapidity. The value of \( \beta = \frac{v}{c} \) (where \( v \) is the velocity of the particle and \( c \) is the speed of light) is given by \( \beta = \tanh y \). The value of \( \gamma \) (\( \gamma = \sqrt{1 - \beta^2} \)) is given by \( \gamma = \cosh(y) \). Also, the product of \( \beta \) and \( \gamma \) can be expressed as \( \beta \gamma = \sinh(y) \). The projectile at AGS energies travels at \( \beta = 0.99795 \) and \( \gamma = 15.61 \). Hence the need for relativistic variables. In the limit where the particle mass is negligible, or when the momentum and transverse momentum are much greater than the mass, the rapidity can be approximated by a variable called the pseudorapidity, \( \eta \). The pseudorapidity is defined as \[ \eta = \frac{1}{2} \ln \left( \frac{1 + \cos(\theta)}{1 - \cos(\theta)} \right) = \ln \left( \tan \frac{\theta}{2} \right), \] where \( \theta \) is again the angle of the particle in spherical coordinates with respect to the beam direction. The pseudorapidity is particularly useful when the particles cannot be completely identified by the experimental apparatus.

Measurements are also made in the direction transverse to that of the projectile velocity. The observable used for these measurements is the transverse momentum of the particle, \( p_t \), which is simply the projection of the particle momentum onto the transverse axis. A related variable is the transverse mass, given by \( m_t = \sqrt{p_t^2 + m_0^2} \), where \( m_0 \) is the rest mass of the particle. The energy of a particle can be determined from the transverse mass using \( E = m_t \cosh(y) \). Also commonly used is the transverse kinetic energy given by \( T_t = m_t - m_0 \).
This dissertation presents results examining the distributions of protons and neutrons emitted into the forward direction after a relativistic heavy ion collision. Much can be deduced about the dynamics of the reaction by observing the resulting momentum, rapidity, and multiplicity of these nucleons after the collision. These measurements will provide information about the amount of energy deposit in the reaction system, as described below.

By using nucleons as a probe of the collision, it can be determined if the energy deposition in the collision is sufficient for QGP formation, along with the extent of transparency of the collision. As illustrated in Figure 1.2, the colliding nuclei are expected to stop each other at AGS energies, indicating that there is a small amount of transparency in these collisions - the nuclei are opaque to each other. A small transparency indicates that there are many interactions taking place involving most or all of the initial nucleons with each interaction depositing energy into the system, thus increasing the energy density of the system and creating a more favorable environment for QGP formation. This dissertation will attempt to confirm this scenario by simply measuring the number, or multiplicity, of projectile nucleons that traverse the diameter of the target nucleus without participating in an interaction, even though these nucleons are members of the participant volume. From this number, the interaction cross section of the projectile nucleons with the target nucleus can be extracted and the energy density of the system can be estimated. A lack of transparency in these collisions can be inferred if few nucleons uninvolved in interactions are identified after the collision. The number of surviving nucleons will be studied as a function of impact parameter. The number of surviving nucleons is expected to decrease as the impact parameter decreases, since the nucleons have to traverse a longer geometrical path across the target nuclear
volume at smaller impact parameters. This analysis is not aimed specifically at identifying the existence or non-existence of a QGP. Instead, it strives to determine if conditions are favorable for QGP formation in heavy ion collisions at AGS energies.

Another question that can be answered by studying nucleon distributions is whether or not there is a thermally equilibrated system created in the collision. This would be seen in the presence of a QGP, or even in the presence of a hot hadronic gas in the system. If a thermalized system is produced, particles emitted from the system should have momenta distributed according to a Boltzmann thermal distribution, or \( f(p) = C_B \cdot m_t \cdot e^{-m_t/T_B} \), where \( C_B \) is a normalization constant, \( m_t \) is the transverse mass of the particle, and \( T_B \) is the Boltzmann temperature of the system. This dissertation will measure the transverse mass of protons and will fit these distributions to the Boltzmann distribution and extract the Boltzmann temperature of the possibly thermalized system as a function of rapidity. Of course, the higher the temperature of the system, the higher the chance for QGP formation, as can be deduced by examining Figure 1.1.

Figure 1.4 shows schematically what is expected for the rapidity and transverse mass spectra at different impact parameters. For more peripheral collisions, where the energy deposited into the system should not be very large, any thermalized system produced would have a low temperature, which is characterized by a steep slope in the transverse mass spectrum. The more central collisions should produce hotter systems characterized by a more shallow slope in the transverse mass spectrum. There will be instances where the transverse mass spectrum will cover contributions from both the participant and spectator systems. In this case, both slopes should be seen with the spectator contribution dominating at low transverse mass.
Measurement of the nucleon rapidity distributions, dN/dy, as a function of impact parameter is made in order to determine where the nucleons are located in rapidity after the collision. The more each nucleon shifts in rapidity during the reaction, the more energy is deposited into the colliding system. For peripheral collisions, with no overlap between the target and projectile nuclei, the dN/dy distribution will contain two peaks: one at the target rapidity and one at the projectile rapidity, as shown in Figure 1.4. The number of nucleons in each of these peaks equals the number of initial nucleons in each nucleus. As the impact parameter decreases and the nuclei begin to overlap, the nucleons will begin to collide and interact, resulting in shifts in the nucleon rapidity towards the middle rapidity of the system. This will tend to decrease the number of nucleons in the original nuclei dN/dy peaks and the nucleons will begin to fill in the gap between the target and projectile rapidity. The extent of this effect increases as the impact parameter decreases to zero, with the initial rapidity peaks possibly disappearing altogether if there is a low degree of transparency in the collision. This dissertation will not attempt to measure the full breadth of the dN/dy spectrum, but will present rapidity distributions near the projectile rapidity in order to determine the extent of transparency.

In summary, this dissertation will study the extent of "stopping", or transparency, in heavy ion collisions at 14.6 GeV/A. This study will extract the rapidity densities, dN/dy, of protons. Also, the Boltzmann temperatures of the system will be measured as a function of the rapidity. These complementary measurements will help characterize the densities and temperatures of the matter being created in these collisions.
<table>
<thead>
<tr>
<th>Geometry</th>
<th>Centrality</th>
<th>Rapidity</th>
<th>$p_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>![Sphere]</td>
<td>Low $E_t$</td>
<td>![Histogram] $y_1$ ![Histogram] $y_p$</td>
<td>$E \frac{d^2N}{dp^2}$</td>
</tr>
<tr>
<td>![Sphere]</td>
<td>Mid $E_t$</td>
<td>![Histogram] $y_1$ ![Histogram] $y_p$</td>
<td>$E \frac{d^2N}{dp^2}$</td>
</tr>
<tr>
<td>![Sphere]</td>
<td>High $E_t$</td>
<td>![Histogram] $y_1$ ![Histogram] $y_p$</td>
<td>$E \frac{d^2N}{dp^2}$</td>
</tr>
</tbody>
</table>

Figure 1.4: Expected nucleon rapidity and transverse momentum spectra as a function of centrality.
CHAPTER 2: EXPERIMENTAL APPARATUS

The data presented in this dissertation were taken with the apparatus and resources of Experiment E814, which is a collaboration of about fifty physicists from the following institutions: Brookhaven National Laboratory, Los Alamos National Laboratory, McGill University, University of New Mexico, University of Pittsburgh, University of São Paulo, SUNY Stony Brook, University of Tel Aviv, Texas A&M University, and Yale University. E814 operates at the Brookhaven National Laboratory Alternating Gradient Synchrotron and is a very versatile experiment studying phenomena associated with both peripheral and central collisions while also searching for various exotic particles. This chapter will describe in detail the detectors making up E814 along with a brief synopsis of the physics that has been accomplished by the collaboration.

2.1: E814 OVERVIEW

Experiment E814 was initially designed to study processes associated with peripheral collisions, such as Coulomb Dissociation. In peripheral collisions, the projectile nucleus passes through the electromagnetic field of the target nucleus. At relativistic speeds, the projectile sees this field as a narrow, Lorentz contracted electromagnetic impulse that excites the projectile, predominantly into its giant dipole resonance. In the giant dipole resonance, the protons and neutrons of the nucleus effectively oscillate within the nucleus in such a manner that the neutrons are separated from the protons. If the projectile then fragments, it is probable that it will fragment into very neutron or proton-rich nuclei.\(^{14,19}\)
E814 has also conducted a search for exotic particles, such as strangelets. Strangelets are particles containing a number of up, down, and strange quarks in a single quark bag, which is an energetically favorable configuration compared to hadrons. Strangelets could be formed in the presence of a quark-gluon plasma. The E814 search has thus far been able to set upper limits for strangelet production at the level of less than $1.2 \times 10^{-4}$ multiply charged strangelets and less than $8.3 \times 10^{-4}$ singly charged strangelets, per interaction, at the 90% confidence level. E814 has also studied the production rates of antiprotons as a function of the centrality of the events to determine to what extent the antiprotons are absorbed in the target nucleus. Currently being studied is the production, probably via coalescence, of deuterons, tritons, and $^3$He near the mid-rapidity region. Studies of this type are ways to probe the high density and freeze-out stages of the heavy ion collisions.

This dissertation will concentrate on studies of central collisions using the E814 apparatus. These studies have previously been performed by E814 using an examination of global observables such as transverse energy and charged particle multiplicity distributions, which provide a means by which to characterize each event. Studies of this type will be extended here by measuring distributions of nucleons as a function of these observables.

The E814 apparatus is shown schematically in Figure 2.1. The figure is divided into three sections: a beam-defining section, a target section, and the forward spectrometer. Directions along the beam, in analogy to the flow of water in a stream from left to right on the schematic, will be referred to as upstream (towards the left of the figure) and downstream (towards the right). The coordinate system used here has its z-axis pointing in the direction of the beam. The y-axis points out of the page in Figure 2.1. The x-axis then points up on the figure in the direction that negatively charged particles are deflected by the spectrometer magnets.
Figure 2.1: The E814 experimental apparatus divided into the beam defining region, the target region, and the forward spectrometer. For scale, the forward scintillators are 14.7 m and 31.3 m from the target.
There are two different configurations of the E814 apparatus implemented to obtain the data presented in this dissertation. The closed geometry, used during the 1989 data taking period, is as shown in Figure 2.1 with the exception that the beam vertex detectors were not present. The open geometry was implemented for the 1991 data taking period and was identical to the closed geometry except for the following: the beam vertex detectors were present, the Participant Calorimeter was removed and replaced by a lead collimator, DC1 was removed, and the second magnet was removed and the other magnet was repositioned. The reasons for these changes in the detector geometry will be explained later.

The beam-defining section of the apparatus consists of a set of plastic scintillators (abbreviated by BSCI) and a pair of silicon vertex detectors (BVER) located upstream of the target.

Event characterization is performed by the detectors surrounding the target. Just downstream of the target are a set of two silicon multiplicity detectors (MULT) designed to measure the charged particle multiplicity of the events. Surrounding the target are five walls of the Target Calorimeter (TCAL), whose purpose is to measure the transverse energy of the event. The Participant Calorimeter (PCAL) lies downstream of the Target Calorimeter and also measures the transverse energy, but over a different range of pseudorapidity than the TCAL. There is a small opening in the Participant Calorimeter through which the beam must pass in order to enter the forward spectrometer region.

The forward spectrometer serves to fully identify particles that traverse it. The spectrometer consists of two bending magnets for momentum analysis. Particle tracking is accomplished by the three tracking chambers, labelled DC1, DC2, and DC3. The charge and time-of-flight of the particles is measured by a scintillator hodoscope (FSCI) located downstream from the tracking chambers. Further downstream lie the uranium calorimeters (UCAL) that measure the energy of the
particles. From the information the spectrometer provides, it is possible to fully identify and characterize the particles entering the spectrometer.

2.2: DETECTOR DESCRIPTIONS

This section will review each detector of the E814 apparatus in more detail. When possible, the detectors will be described in order from upstream to downstream.

The beam scintillator system serves to identify a valid beam particle arriving at the target. It also provides the timing reference for the event, called \( t_0 \). This system consists of four plastic scintillators labelled S1, S2, S3, and S4 on Figure 2.1, located at 652.8 cm, 627.4 cm, 203.2 cm, and 177.8 cm, respectively, upstream from the target. S2 and S4 both intersect the beam, and a coincidence between these two detectors defines a beam event. S2 is viewed by four Thorn-EMI 9954 phototubes set 90 degrees apart from each other. S4, which is used to provide the time reference with a resolution of 130 psec, is viewed by two Hamamatsu R-2076 phototubes. These phototubes have better timing resolution than the Thorn-EMI tubes. S1 and S3 are annular detectors that serve to veto events in which S1 or S3 detect a signal. These scintillators are each viewed by two of the Thorn-EMI phototubes.

For the 1991 data taking period, two beam vertex detectors were installed to provide accurate measurement of the position and angle of the beam particles before they reach the target. Each of these detectors is a silicon detector consisting of 320 strips of 200 micron thick silicon with a 50 micron pitch. The two detectors are placed within the path of the beam between the beam scintillators S2 and S3.
and are separated by 5 meters. These detectors provide a measurement of the position of the beam particle at the target to within 50μm.

The Target Calorimeter, or TCAL, is constructed in five walls of NaI(Tl) crystals surrounding the target as shown in Figure 2.2a. The TCAL consists of a total of 992 crystals aligned in 52 rows with each crystal measuring 13.8 cm (5.3 radiation lengths or 0.33 interaction lengths) along its longest dimensions and arranged to point towards the target as shown in Figure 2.2b. The most upstream wall has a 3 x 3 block of crystals removed from its middle to allow passage of the beam. Details of the construction and testing of this detector are covered in a colleagues' thesis. The purpose of the TCAL is to measure the transverse energy of particles in the pseudorapidity range $-2.0 < \eta < 0.8$. This detector is used as a centrality measure in the nucleon measurements. Figure 2.3a shows the measured transverse energy cross sections from the TCAL for 14.6 GeV/A $^{28}$Si incident on targets of Pb, Cu, and Al. The results have been discussed in detail elsewhere. A description of the use of this detector in the trigger will be given later.

A study of the correlation of the transverse energy measured by the TCAL and the impact parameter of the collision was performed by L. Waters. The HIJET event simulator, which simulates heavy ion collisions at AGS energies, with rescattering was used in conjunction with the GEANT package (both described in more detail later) to simulate what the TCAL measures $E_t$ as a function of the impact parameter input to the HIJET code for Si + Pb collisions at AGS energies. The results are shown in Figure 2.4. The vertical axis of the plot is the impact parameter in units of fermis and the horizontal axis is the transverse energy in GeV seen by the TCAL. The $E_t$ values shown on this plot must be divided by two in order to obtain the true measured TCAL $E_t$, since the TCAL is not a completely hermetic calorimeter due to its small thickness. Figure 2.4 illustrates that the TCAL characterizes the impact parameter of an event to within about two fermi.
Figure 2.2: Schematic of the E814 Target Calorimeter. a) view upstream along the beam axis showing the arrangement of the five walls. b) view from above emphasizing the projective arrangement of the NaI crystals.
Figure 2.3: a) Transverse energy cross sections detected by the TCAL for Si + Pb, Cu, and Al collisions. b) Charged particle multiplicity cross sections detected by the MULT for all three targets. The smooth lines (Pb target only in (b)) are Landau fireball model predictions of the distributions. In b), the dashed lines are HIJET with rescattering predictions.
Figure 2.4: The impact parameter dependence of twice the transverse energy measured by the TCAL as calculated by HIJET with rescattering for Si+Pb collisions.

Figure 2.5: Correlation of the TCAL transverse energy and the MULT charged particle multiplicity for Si + Pb collisions.
Figure 2.6: Schematic of the E814 Silicon Multiplicity detector. a) dimensions of the detectors. b) segmentation of the detector pads.
Figure 2.7: Schematic of the E814 Participant Calorimeter. The four wedges are stacked to create a hole through which particles enter the forward spectrometer. Phototubes are mounted on the edges.
The Target Paddles, or TPAD, are a set of 52 plastic scintillator strips lining the inside of the walls of the Target Calorimeter as shown in Figure 2.2b. Each TPAD scintillator is positioned parallel to the z-axis and lies directly over one of the 52 rows of TCAL crystals. Each scintillator strip consists of a $0.64 \times 3.5 \times 49 \text{ cm}^3$ slab of BC400 scintillator material viewed by an EMI 9127B phototube. The TPAD serves to measure the charge of particles passing into the TCAL and also to prevent low-energy delta electrons from entering the TCAL. The number of TPAD strips that detect a signal during an event is used as a crude fast multiplicity measurement in the definition of the interaction trigger described later.

The silicon multiplicity detector, or MULT, is constructed as two disks of 300 $\mu$m thick silicon wafers, each segmented into 512 pads as shown in Figure 2.6. Each wafer is annular to allow passage of the beam and arranged so that there is no overlap in their projections from the target. The first detector is located 51.4 mm downstream from the target and has its pads arranged into 8 annular rings. The second detector, located 98.3 mm downstream from the target, is arranged into 12 annular rings. The purpose of the multiplicity detector is to measure the multiplicity, or the number, of charged particles in the pseudorapidity range $0.9 < \eta < 3.9$ as a further measure of the centrality of the event. The charged particle multiplicity cross sections for 14.6 GeV $^{28}\text{Si}$ incident on targets of Pb, Cu, and Al are shown in Figure 2.3b. The description of the use of this detector in the centrality trigger is covered later. A more thorough explanation of the implementation and calibration of this detector is described elsewhere.21

The charged particle multiplicity measured by the MULT detector is used as an additional measurement of the impact parameter, which is possible due to the correlation between the charged particle multiplicity and the transverse energy. A plot of this correlation for 14.6 GeV Si + Pb collisions is shown in Figure 2.5.
The participant calorimeter, or PCAL, is designed to measure the transverse energy in the same pseudorapidity range as the silicon multiplicity detector. A schematic of this detector is shown in Figure 2.7. The PCAL is constructed as four wedges that can be arranged to form a variable size rectangular aperture about the beam. The PCAL is a sampling hadronic calorimeter segmented into 16 azimuthal, 8 radial, and 4 depth segments. The four depth segments consisted of two electromagnetic segments and two hadronic sections contributing to the detector's 4 interaction length depth. The electromagnetic segments consist of lead as an absorber while the hadronic section utilizes both lead and iron absorbers. All four segments are read out with plastic scintillators sandwiched between the absorbers with the signals being carried out of the PCAL to the phototubes via wavelength shifting optic fibers. This detector was not implemented during the 1989 data run, so no $E_t$ measurement was obtained from the PCAL during this running period. The PCAL was removed during the 1991 data taking period to increase the acceptance of the forward spectrometer, which is the reason that running period is referred to as the open geometry run. Essentially, the PCAL serves only as a collimator of particles into a rectangular opening 6.4 cm wide in horizontally and 4.1 cm wide vertically centered about the beam, providing an opening of roughly the forward 0.8 degree cone as seen from the target into the spectrometer during the closed geometry run. Details of the construction of the PCAL are described elsewhere.23,24.

The forward spectrometer contains three tracking chambers whose purpose is to measure the position of charged particles in the spectrometer. Together with the knowledge of the magnetic field and charge, the particle momentum can be determined. A detailed description of the drift chambers will be given later in this chapter.
The spectrometer includes three sets of scintillator hodoscopes located downstream from the drift chambers. There is a set of four BC404 plastic scintillator slats, each of dimension 10 cm x 0.6 cm x 1 m, positioned to intercept negatively charged particles like the proposed pion or negative kaons. These scintillators are located 14.7 m downstream from the target and start at 65 cm in the positive x direction. There is also a set of six scintillator slats with the same dimensions positioned to intercept protons. These "proton" scintillators are also located 14.7 m downstream from the target and start at 14.7 cm in the negative x direction. In addition, there are 44 scintillator slats of dimension 10 cm x 1.2 m x 1 cm positioned 31.31 m from the target. Each scintillator slat is viewed on each end by a Thorn-EMI 9954B phototube as shown in Figure 2.8a. The signals from the phototubes are fed into both TDCs and ADCs to extract pulse height and timing information. The ratio of the ADC values read from each end of the scintillator are used to determine the vertical position of the particle along the scintillator length with a resolution of 3 cm. The timing signal obtained by averaging the time signal from both phototubes has a resolution of 300 ps. The charge of the particle is determined from the pulse height information, where it is a simple matter to separate charge one from charge two and greater particles since the minimum ionizing signal is separated from the pedestal by more than five standard deviations.

The uranium calorimeters, or UCAL, are a total of 25 calorimeter modules placed downstream of the forward scintillators. Each calorimeter module is 120 cm high, 20 cm wide, and 75 cm long (4.2 interaction lengths deep) as shown in Figure 2.8b. Each calorimeter module is further segmented into 12 optically decoupled towers that are 20 cm high and 10 cm wide with phototubes mounted on the rear of each tower. The five upstream modules are located 12.68 m downstream from the target while the rest lie 36.31 m from the target. The UCAL detector utilizes uranium and copper plates as absorbers with scintillator sheets placed between the
Figure 2.8a: Schematic of an E814 forward scintillator showing phototubes mounted on both ends.

Figure 2.8b: Schematic of an E814 uranium calorimeter module. Phototubes are mounted in the rear.
layers of absorber. The scintillator signals are then relayed to the photomultiplier tubes in the rear of each module via wavelength shifting bars. These detectors measure the energy of neutrons with an energy resolution of
\[ \frac{\Delta E}{E_{\text{rms}}} = 0.4 \frac{1}{\sqrt{E(\text{GeV})}}. \]
The position resolution for an isolated particle hit of 12 GeV in the UCALs is 1.3 cm horizontally and 1.8 cm vertically. Since the drift chambers and forward scintillators provide all of the required information for the identification of charged particles, the UCAL was not used in the proton analysis, but was essential for the pion search. More details of the construction and calibration of the UCAL system are described elsewhere.

2.3: DRIFT CHAMBERS

The drift chambers provide a sensitive measurement of the magnetic rigidity of the charged particles in the spectrometer. This measurement is essential for the high resolution of the proton data presented in this dissertation. This section will describe the construction and performance of the drift chambers in detail.

The forward spectrometer consists of three tracking chambers that provide the position information necessary for determining the momentum of charged particles traversing the spectrometer. The first tracking chamber, called DC1, is exclusively a segmented cathode pad chamber while the other tracking chambers, DC2 and DC3, are combination pad and drift chambers. These detectors are located 3.96 m, 6.92 m, and 11.56 m, respectively, downstream from the target. The drift chambers are designed to contain as little mass as possible to optimize momentum resolution and prevent interactions within the chambers. DC3 is only
1.9\% of a radiation length thick, while DC1 and DC2 are less than 0.7\% of a radiation length thick.

The construction of the DC2 and DC3 tracking chambers, which are identical with the exception of their size, is illustrated in Figure 2.9. The tracking chambers consist of 18 G-10 rectangular planes, each with a rectangular "window" in their center containing either mylar or wires, all pressed together to form the final product. The outside planes of the chambers are clear mylar windows that contain the gas within the chamber. The next twelve upstream planes make up the drift section of each chamber, which consist of six doubly aluminized mylar windows alternated with six planes containing the wires. Downstream from the drift section lies the pad section, which consists of a doubly aluminized mylar plane, followed by a wire plane, with the cathode pad plane at the rear. The drift and pad sections are separated by one doubly aluminized mylar plane. The chambers are assembled by lining the outside of each G-10 plane with a rubber sealing strip that has adhesive on one side to adhere it to the plane. Each plane is then pressed together and bolted in place. The gas seal thus created is sufficient to hold gas slightly above atmospheric pressure. In addition, each plane containing wires has three gas feedthroughs on each end of the plane. The chamber gas is fed into one end of the chamber from a gas manifold attached directly to the chamber that receives gas from the gas handling system located outside of the experimental area. The gas exits the opposite end of the chamber in order to provide constant circulation. The gas used for all data taking shown here was a mixture of 50\% argon and 50\% ethane, chosen for its drift velocity properties. Also, the gas was bubbled through alcohol in order to help reduce the radiation damage seen in many drift chambers.27

Table 2.1 lists the specification of the drift sections for both DC2 and DC3, illustrating the size difference in the two detectors. Figure 2.10 shows a schematic of the drift cells of each chamber. Each drift section consists of six planes of
Figure 2.9: Schematic of the construction of DC2 and DC3 showing the locations of the six wire planes and the pad plane within the detector.
### E814 Drift Chamber Specifications

<table>
<thead>
<tr>
<th></th>
<th>DC2</th>
<th>DC3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance from target</td>
<td>6.92m</td>
<td>11.56m</td>
</tr>
<tr>
<td>Active area</td>
<td>30x80cm</td>
<td>50x200cm</td>
</tr>
<tr>
<td>Number of drift planes</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Sense wires per plane</td>
<td>128</td>
<td>160</td>
</tr>
<tr>
<td>Field wires per plane</td>
<td>129</td>
<td>161</td>
</tr>
<tr>
<td>Anode-field wire spacing</td>
<td>3.175mm</td>
<td>6.35mm</td>
</tr>
<tr>
<td>Anode-cathode spacing</td>
<td>3.175mm</td>
<td>6.35mm</td>
</tr>
<tr>
<td>Number of TDC channels</td>
<td>768</td>
<td>960</td>
</tr>
<tr>
<td>Type of gas</td>
<td>50% Argon/50% Ethane</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.1: Specifications and dimensions of the drift sections for DC2 and DC3. Note their differences in size.

\[ s = 3175 \text{ microns (DC2)} \]
\[ s = 6350 \text{ microns (DC3)} \]

Figure 2.10: Schematic of a drift cell of DC2 and DC3.
alternating 17.5 μm diameter gold-plated tungsten "anode" or "sense" wires and 125 μm diameter stainless steel "cathode" or "field" wires. DC2 contains 128 anode and cathode wires per plane, while DC3 has 160 per plane. Each of the six wire planes are separated by a 25 μm thick doubly aluminized mylar cathode foil set at a high negative voltage in order to shape the electric field in the drift section and to stop the spread of delta electrons from plane to plane. The anode wire to cathode wire distance, which is identical to the wire to foil distance, is 3.18 mm in DC2 and 6.35 mm in DC3. In addition, the anode and cathode wires are staggered from drift plane to drift plane to help resolve the left-right ambiguity described later. Each wire is placed vertically so that the positions of charged particles are measured by the drift sections in the x direction. This measurement is accomplished as follows: The charged particle passes through the drift plane, ionizing particles in the gas as it passes. The cathode wires are set at a high potential (typically -1200 volts) so that the ionization charge drifts towards the anode wire with a drift velocity of 50 μm / nsec in the 50% / 50% Ar-ethane gas. This drift velocity produces a maximum drift time of approximately 65 nsec in DC2 and 130 nsec in DC3. When the ionization charge approaches the anode wire (typically set at 0 volts), an "avalanche", or multiplication of charge occurs since the ionization charge now further ionizes the gas in this region. The avalanche charge is deposited onto the anode wire and sent out to the electronics chain.

When operating in a relativistic heavy ion environment, there are special problems that a drift chamber design must overcome. One of these problems is that the chamber must be able to simultaneously track up to 14 charged particles in a single event. This is accomplished here by having a high segmentation, or a large number of wires in each plane. Another problem is that the drift chambers must lie within the path of the beam, which is particularly difficult for drift chambers since the beam particles deposit a very high amount of charge into the chamber. This
problem is solved by electronically isolating a set of six field wires per plane that are in the beam path. These wires are then set at a -200 volts to reduce the charge amplification in this region.

In an experiment designed to measure peripheral collisions, it is desirable to be able to track particles ranging from minimum ionizing particles up to the charge 14 silicon ions. This is difficult for drift chambers since the ionization charge deposited increases as $Z^2$ of the particle depositing the charge. In other words, the silicon ions will deposit 196 times more charge than a proton. This dynamic range problem is solved by the use of the very thin 17 $\mu$m diameter anode wires. When an avalanche occurs around the very thin anode wire, space charge fields are created that counteract the applied field, thus lowering the gas gain. This effect reduces the dynamic range requirements on the electronics chain. This saturation has been tested using the DC1 chamber by measuring the amount of charge deposited on the anode wire as a function of the voltage applied to the wire for the Si beam, proton beam, and a 5.4 keV X-ray beam. These results are shown in Figure 2.11. With the thin wire, the ratio between the charge deposited by the silicon ions and minimum ionizing particles has been reduced from 200 to about 80.$^{28}$

The resolution of the drift chambers was measured using both a 14 GeV proton test beam and a $^{28}$Si beam from the AGS. The single-particle single-point position resolution of the $^{28}$Si beam is determined to be 120 $\mu$m RMS for DC2 and 140 $\mu$m RMS for DC3 using a reduced voltage on the wires in each chamber. The single-point silicon resolution for DC2 and DC3 running at a voltage where the detectors are sensitive to both heavy ions and minimum ionizing particles is 260 $\mu$m. The resolution curves measured using the Si beam by taking the deviations from a straight line fit using all but one plane are shown for DC2 and DC3 in Figure 2.12a,b. For the magnetic fields used in the closed geometry data taking run, this
Figure 2.11: DC1 anode charge vs. anode voltage as measured with an X-ray source, a proton beam, and a $^{28}\text{Si}$ beam. The saturation effect from the space charge can be seen. Without any charge saturation the anode charge ratio between the Si beam and the proton beam to be 200.
Figure 2.12: Position and momentum resolutions of the drift chambers. a) Position resolution of the DC2 drift section. b) Position resolution of the DC3 drift section. c) Measured proton beam momentum using DC2 and DC3. The momentum resolution is typically 0.02%.
Figure 2.13: Schematics of the drift and pad section electronics chains.
translates to a momentum resolution of the 14 GeV proton test beam of \(\Delta p / p^2 = 0.02\%\) as shown in Figure 2.12c.

The electronics chain for the drift section consists of BNL-designed hybrid electronics and LeCroy FASTBUS digitization electronics shown in Figure 2.13a. The signal from the anode wires is fed into a low noise common-base pre-amplifier mounted on the outside of the chamber near each anode wire. The pre-amplifier signal is then fed into a unipolar shaping amplifier, located outside of the experimental area, with a gain of 2000 and a rise-time of 12 nsec. The signal from the shaping amplifier goes into a two-level, or dual discriminator circuit.

The dual discriminator is included in the electronics chain in order to help distinguish between minimum ionizing particles and particles with charge two or greater. To accomplish this, the lower of the two dual discriminator levels is set slightly above the noise level from the drift chamber anode wires. If the amplitude of a pulse is greater than this threshold, but not the upper level threshold, it is from a minimum ionizing particle and the dual discriminator outputs a single 50 nsec wide digital pulse whose leading edge corresponds to the time the first electron cluster from the ionizing track reaches the anode wire. The upper level threshold is set slightly above the pulse height of a minimum ionizing particle. The upper level discriminator further shapes the 12 nsec unipolar pulse from the amplifier into a 40 nsec risetime bipolar pulse before sending the signal into a zero-crossing discriminator. The shaping stage of the high level discriminator has a gain of one. If the signal passes both the low and high discriminator levels, the discriminator produces two 50 nsec pulses approximately 160-200 nsec apart where the exact time of the second pulse with respect to the first one marks the position of the centroid of the total primary charge that drifted onto the anode wire.

The signal from the discriminator is fed into a 10-bit, pipeline LeCroy 1879 time-to-digital converter (TDC) that has a one nsec resolution. The pipeline
feature of the TDC allows the detection of the two or more discriminator pulses, if present. The pipeline is a 10-bit word that is shifted by one bit every nanosecond. Each time the bits are shifted, a new bit is added to the end of the word. There is a discriminator threshold present in the TDC. If the pulse height sent into the TDC goes above that threshold when the pipeline is shifted, a one is deposited in the least significant bit, otherwise a zero is deposited there. A single firing of the dual discriminator will be seen in the pipeline as a series of ones bracketed by zeroes. The double firing will be seen as two series of ones separated by a series of zeroes. The pipeline TDC will not allow the detection of more than one charged particle track on the same wire since the separation of those hits will typically be shorter than the shaping time.

The electronics chain utilizes bipolar amplifiers since the area balance in the bipolar pulse eliminates baseline shifts at the high rates seen by these chambers. The unipolar amplifiers are used since fast rise times are required to accurately determine the drift times of the electron clusters.

All three tracking chambers contain a pad section consisting of an aluminized mylar cathode foil, a plane of vertical anode and cathode wires, and the cathode pad plane. When an ionizing particle passes through the pad section, the deposited ionization charge drifts toward the anode wire where an avalanche occurs. An image charge from the avalanche is generated covering an area the size of two or three pads on the cathode pad plane. The position of the track along the wire is then determined by finding the centroid of the image charge. An example of the correlation of the charge deposited on neighboring pads is shown in Figure 2.14, which is obtained using a proton beam in the DC1 pad chamber. The pad with the maximum amount of charge deposit is located and its charge is labelled $Q_{\text{max}}$. The charge on the pads adjacent to this one are labelled $Q_{\text{left}}$ and $Q_{\text{right}}$. By plotting the ratios $Q_{\text{left}} / Q_{\text{max}}$ and $Q_{\text{right}} / Q_{\text{max}}$, a hyperbolic shape is produced whose width
corresponds to the position resolution. The track position perpendicular to the wire is only determined to within the width of the wire drift cell.

The cathode planes in DC2 and DC3 are large 3-layer copper clad FR-4 printed circuit boards that each have a chevron pattern etched on the surface that faces the wire plane, as shown in Figure 2.9. The chevron pad geometry is illustrated in Figure 2.15b. Each copper chevron has a plated through hole that connects it to the back layer of the printed circuit board, which contains wire traces that carry the signals out of the chamber to the preamplifiers. The chevrons are arranged in columns and are positioned such that their centers are located immediately below the anode wires in the wire plane. Each column of chevrons is separated by an inactive guard strip that helps shape the electric field so that less than 10% of the charge induced on a pad column leaks to a neighboring column.

A gain constant to better than 10% must be maintained over the entire surface of the cathode pad plane, so it is necessary to keep the cathode pad to anode wire distance constant to within 2%. This degree of flatness is obtained by backing the pad plane with 4.68 mm thick Nomex honeycomb backed with a 200 μm thick sheet of G-10 material. This technique adds less than 0.15% of a radiation length to the drift chamber mass and successfully provides the required flatness.

DC1 was constructed with a slightly different design as shown in Figure 2.15a.30 The DC1 pad plane is a three layer printed circuit board made of copper-clad polymide. Rows of 2 mm x 0.9 mm rectangular copper pads run directly beneath each anode wire and are separated from each other by guard strips that lie below the field wires. Each row of pads has a continuous line of resistive ink running along its length, laser trimmed for resistive consistency. One out of every 4, 8, or 10 pads in a row, depending on the pad segmentation, is connected by a plated-through hole to the traces on the back layer of the pad plane. The position of the track is again determined by finding the centroid of the image charge deposited
Figure 2.14: Charge ratio plot from DC1 using a 14 GeV proton beam. The position resolution determined from the width of the hyperbola is 120 μm (rms).
Figure 2.15: Diagram of the pad geometry used for DC1 and DC2/DC3. 
a) Diagram of the DC1 pads illustrating the resistive charge division technique. 
b) Diagram of the DC2 and DC3 pads illustrating the geometric charge division technique.
Figure 2.16: Schematic of the electronics modules used in the drift chamber pulser calibration system.
along a row of pads. The difference here is that the centroid is now determined by a resistive charge division instead of the geometric charge division technique used with DC2 and DC3.

The electronics chain for the pads is shown in Figure 2.13b. The signals from the pads are sent into charge sensitive pre-amplifiers mounted on the tracking chambers. The pre-amplifier signals are fed into a shaping amplifier whose output is a bipolar pulse with a 200 nsec risetime that is sent into a 15-bit LeCroy 1885F analog-to-digital converter (ADC), where the signal amplitudes are digitized.

The resolutions of the pad chambers were studied using a 14 Gev proton beam provided by the AGS. The single particle resolution of DC1 has been measured to be 120 μm RMS along the anode wire. The DC2 resolution is better than 4 mm RMS. A rule of thumb is that a pad chamber resolution is typically about 5% of the length of the pad.29

In order to calibrate the drift sections of DC2 and DC3, it is necessary to convert the time pulses received by a TDC into the distance between the ionizing track and the anode wire, in microns. This distance is then converted into the E814 coordinate system for track reconstruction. Also, for the pad sections, a calibration of ADC channel with charge deposited on the pad is needed along with the ADC pedestal. The calibration system implemented to obtain the time-to-distance relationship and the pad ADC value to charge relationship is described below.

A schematic of the drift chamber calibration system is shown in Figure 2.16. The system generates test pulses to simulate the charged particle hits using a pulser designed by the BNL Instrumentation Division. The amplitude of the pulse generated by the pulser is user-controllable through a CAMAC interface. The pulser signal is then fed into a set of CAMAC switching modules that were designed by the University of Pittsburgh Instrumentation Division. These modules allow the user to select which drift plane or pad section of either of the drift chambers to
pulse. The pulse travels from the switching modules directly into the calibration pulser leads installed directly on the electronics boards of each drift chamber plane. From there, the pulses pass through the same electronics chain as the ionized particle signals all the way to the ADC and TDC modules.

The calibration of the drift sections is slightly more complicated due to the dual discriminator feature of the electronics chain. Here, the voltage setting of the lower discriminator is first read. The pulser is then stepped from below this setting to above this setting. The TDC channel at which the pulser amplitude crosses the lower threshold is recorded to obtain the relative zero times for each wire, which vary due to differing connection and cable lengths. This procedure is repeated for the upper discriminator voltage setting. This type of calibration is especially helpful in locating faulty electronics channels.

The relationship between the time recorded by the TDC and the distance of the charged particle from the wire must also be performed using the AGS proton test beam at 14 GeV. Knowing the distance between the sense wire and the field wire and assuming that the time-to-distance relationship is linear, the plot shown in Figure 2.17 is obtained for DC2, but DC3 yields a similar plot. The nonlinearities at the ends of the data correlation are due to nonlinear drift times both very near and very far from the sense wire. The resolution of the drift chamber on a wire-to-wire basis quoted earlier is also apparent in this plot from the width of the correlation.

Calibration of the pad sections involves relating the pulse height with ADC channel. This is accomplished by scanning the pulse height of the pulser over the ADC range and plotting the linear correlation of the pulser amplitude with the ADC channel. Also, for each ADC channel, a point was plotted for no pulser input to obtain the pedestal of each channel. A linear fit is used to assign a charge to the ionizing particle hitting the pad on a channel-to-channel basis taking the electronics noise, or pedestal, into account.
Figure 2.17: Correlation of the distance of a charged particle from a wire in DC2 against the drift time measured by the TDC. The position resolution is apparent from the width of the band. The line is a straight line fit to the distribution of points excluding the ends.
CHAPTER 3: DATA ANALYSIS

Chapter 3 describes the method used to accumulate and analyze the data presented in this dissertation. Included in this chapter is a description of the trigger used to select the events that are recorded on tape along with a description of how the recorded data is analyzed in order to identify and characterize nucleons in the forward spectrometer.

3.1: TRIGGER

The AGS provides beam projectiles in short bursts called spills. In real time, there are roughly 100,000 beam particles incident on the target during a single AGS spill, which lasts about one second. Each spill is separated by about three seconds. It is not practical to write the information from each detector onto the data tapes for each incident beam particle, or event. Instead, only a small number of the events, usually those that involve a collision with a maximum impact parameter as determined by the TCAL or MULT detectors, are selected. This is done by implementing a trigger system to select which events are to be written to the data tapes. A schematic of the complete trigger system is shown in Figure 3.1. The schematic shows the various decision levels of the trigger system from the initial beam trigger to the communication with the VAX-based data acquisition system (DAQ). Below is a description of how the E814 trigger is set up for the central event running period from which the data in this analysis are taken.

The trigger is implemented as a series of decision levels, all of which must be satisfied for an event to be written to tape. The first of these decision levels is the beam trigger, whose purpose is to decide, within one μsec, if a beam particle is
Figure 3.1: Schematic diagram of the trigger system used for the E814 central collisions running period.
incident upon the target. This is accomplished by examining the pulse height information from the beam scintillator system. This is done by setting a minimum pulse height threshold on the BSCI scintillators located in the beam and requiring that there be a coincidence in the pulse heights of these two scintillators above the threshold. If this requirement is satisfied, then the trigger examines the pulse heights of the veto scintillators within the same time window. If the veto scintillator pulse heights are both below a preset threshold, then the event is considered a valid beam event by the trigger. A number of the events passing the beam trigger are immediately written to tape.

Once it is determined that a beam particle was incident on the target, the next trigger decision level, referred to as the pre-trigger, must determine if a beam particle interacted with the target in some way. The pre-trigger identifies a sample of minimum bias events, that is, it tags events involving an interaction without regard to the impact parameter or other characteristics of the event. The pre-trigger looks at information from the MULT and TPAD detectors, requiring that there be a charged particle multiplicity of at least 15 in the MULT detector and that there be at least 4 hits in the TPAD scintillator paddles. Since the multiplicity thresholds are very low, about 50% of the events passing these requirements are due to events that produce delta rays, or high energy electrons, without a valid interaction taking place. These events are identified in the offline analysis of the events on the data tape.

There is a finite probability that more than one beam particle will pass through the apparatus within a chosen time window, especially if the beam rate is very high. This problem is handled in the Level 1 trigger following the pre-trigger decision. This trigger operates by examining the pulse height of the two BSCI scintillators in the beam after a positive beam trigger decision. If their pulse heights go above a preset discriminator level set above the noise level of the scintillators
during the event, then the event is not written to tape. The Level 1 trigger ensures that there is not a second beam particle traversing the apparatus within 1 \( \mu \text{sec} \) after the beam particle triggering the pre-trigger passes through. This trigger is 99% efficient. The remaining 1% of these double beam events are rejected offline as described later.

The Level 2 trigger is the final trigger level that must be passed for an event to be written on the data tape. This trigger makes use of information from the MULT and TCAL detectors in order to require a minimum centrality on the events being written. Since this trigger must make its decision before the next event begins, the trigger must utilize a very fast electronics system that processes the detector information within 10 \( \mu \text{sec} \) after the pre-trigger decision is made.

The Level 2 trigger based on transverse energy uses information from the Target Calorimeter. This trigger decision involves collecting the amplitude signal from each channel of the side walls of the TCAL and performing an analog sum of these signals. This sum is made with a weight assigned to each NaI channel using a resistor whose resistance corresponds to the sine of the angle that the NaI element makes with respect to the beam direction. The sums are first performed in sets of two rows of NaI channels and fed into the fast Lecroy 4300B FERA (Fast Encoding Readout ADC) modules, where they are digitized. The final analog sums are proportional to the transverse energy generated in the collision.

The TCAL Level 2 trigger is sensitive to three ranges of impact parameter (referred to as low, medium, and high \( E_t \)) for the closed geometry run. Table 3.1 shows the TCAL \( E_t \) range, the trigger cross section represented by each trigger level, and the percentage of the total geometrical cross section covered for the Pb, Cu, and Al targets. Also shown in Table 3.1 are the trigger downscaling factors applied to each trigger so that they would be sampled roughly the same number of times on the data tapes. Only the high \( E_t \) trigger was activated for the open geometry run.
Table 3.1: List of integrated trigger cross sections and downscaling factors for each TCA1 trigger and all three targets.

<table>
<thead>
<tr>
<th>Target</th>
<th>Trigger</th>
<th>( E_t ) range</th>
<th>Trigger ( \sigma )</th>
<th>( % \sigma_{\text{geom.}} )</th>
<th>Down-scaling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb:</td>
<td>Low ( E_t )</td>
<td>6-11 GeV</td>
<td>593 mb</td>
<td>17 %</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>Mid ( E_t )</td>
<td>11-14 GeV</td>
<td>102 mb</td>
<td>3 %</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>High ( E_t )</td>
<td>&gt; 14 GeV</td>
<td>6.9 mb</td>
<td>0.2 %</td>
<td>0</td>
</tr>
<tr>
<td>Cu:</td>
<td>Low ( E_t )</td>
<td>3-5 GeV</td>
<td>1302 mb</td>
<td>58.1 %</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>Mid ( E_t )</td>
<td>5-7 GeV</td>
<td>89.2 mb</td>
<td>3.98 %</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>High ( E_t )</td>
<td>&gt; 7 GeV</td>
<td>4.81 mb</td>
<td>0.21 %</td>
<td>0</td>
</tr>
<tr>
<td>Al:</td>
<td>Low ( E_t )</td>
<td>1-3 GeV</td>
<td>1477 mb</td>
<td>89.6 %</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>Mid ( E_t )</td>
<td>3-5 GeV</td>
<td>36.4 mb</td>
<td>2.2 %</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>High ( E_t )</td>
<td>&gt; 5 GeV</td>
<td>5.33 mb</td>
<td>0.32 %</td>
<td>0</td>
</tr>
</tbody>
</table>

The multiplicity trigger is based on the charged particle multiplicity measured in the silicon multiplicity detector. The measurement of multiplicity is done in the same manner as the trigger \( E_t \) measurement using identical fast FERA modules to that used in the TCA1 trigger. This trigger operates identically to the \( E_t \) trigger in that there are three trigger levels present corresponding to the same percent reaction cross sections quoted above. All three multiplicity trigger levels were implemented during both the closed and open geometry data taking periods.
There were other triggers active in the trigger system during the time the data described here was taken. A random trigger was present that wrote an unbiased sample of random events in order to assist in the calibration of the detectors and to monitor the noise and pedestals of the various detectors. There was also a pulser trigger that allowed a pulser signal to be routed through the detector electronics for calibration purposes. All of these triggers were also activated for data taking without a target present in the target frame, also referred to as an empty target. The empty target data is used to subtract various non-target related backgrounds and to subtract events due to interactions outside of the target. The trigger implemented for the pineut analysis will be described in detail later.

3.2: PATTERN RECOGNITION

Once events are written to tape, they must be analyzed one at a time to identify the particles that traverse the forward spectrometer. The particle's momentum vector is also determined during this process. This task is accomplished by what is called a pattern recognition program. The pattern recognition must take the three-dimensional hit pattern recorded by the E814 detectors and recognize the particle tracks present in the pattern.

The E814 pattern recognition is named "Quanah" after a Comanche Indian chief from Texas, Quanah Parker, who was known to be a very good tracker. Any pattern recognition program should also be a very good tracker. This section will describe the specific pattern recognition techniques and the terms used by Quanah to fully identify and characterize the charged particles in the spectrometer. The general strategy, as illustrated in the Quanah flowchart in Figure 3.2, is to first
Figure 3.2: Flowchart for the E814 spectrometer pattern recognition program, Quanah.
identify tracks and hits within the DC2, DC3, FSCI, and UCAL detectors, which are then connected together to form complete tracks within the spectrometer. The spectrometer tracks can then be projected to the target, allowing determination of the particle identity and momentum.

The philosophy of the Quanah program is to never rule out any possible tracks, so many of the steps of this program actually identify too many tracks. The spurious tracks must be eliminated in a later step. Each track also has a list of pointers associated with it so that the user can follow the reconstruction process back to the initial detector hits that make up the track. Quanah also has an event display that can be seen in some of the figures in this chapter to allow the user to look at the event on a display to determine if Quanah is indeed selecting the proper track. The event display has proven invaluable in the debugging process of Quanah.

Quanah begins its search for complete tracks in the spectrometer by first identifying valid tracks within a single drift chamber, which will be called elements. The input to this section of the program is simply the list of the positions of each hit on each wire plane of the drift chamber as determined from the TDC calibration discussed earlier. A problem with this list is that every physical hit on a drift chamber wire will result in two entries to this list, occurring since the only information available from the wire hit is the drift time, making it impossible to determine whether the particle passed to the left or right of the wire. This is called the left-right ambiguity and must be resolved in the pattern recognition process by first assuming that the particle passed on both sides of the wire and then attempting to determine the correct path the particle took. Identical algorithms are applied to find the groups of hits that make up the elements of both DC2 and DC3 due to their similar construction.

The algorithm Quanah utilizes to find elements in a drift chamber is similar to that used in other experiments, modified for the E814 detectors. The algorithm is
a depth-first, or "tree" algorithm. The tree algorithm operates by starting at a hit on the first plane of the drift chamber, which is designated the base hit. The algorithm next chooses a hit on the adjacent wire plane and connects the two hits with a link. If the slope of the link is too large for a valid track traversing the drift chamber, the link is not considered in the formation of an element and the algorithm moves to the next hit on the second plane, forming a new link between this hit and the base hit. If the link slope is acceptable, a hit on the third adjacent plane is chosen and a second link is formed, again with the requirement that its slope lie within the acceptable range. The next step is to compare these two links sharing the same hit by taking the difference in the slopes of the two links. It is required that the slope difference be small since only straight line tracks are expected in the drift chambers due to the fact that there is no magnetic field present in this region. If the slope difference is large, there is too much curvature in the path and a new second link is chosen, otherwise a third link is formed from a new hit on the next plane. This process of forming, testing, and eliminating links can be thought of in terms of climbing up and down the tree formed by the pattern of the hits, with the links representing branches. The climbing process is continued until the sixth, or top, plane is reached, or until it is found that there is no viable path to climb. If a track is found with a minimum of three hits, then that group of hits is saved as an element. The algorithm has been designed to look for tracks with one or more planes missing in the track to allow for detector inefficiencies, which is accomplished by first looking for all six-hit elements, eliminating the hits contained in these elements, then searching for all five-hit elements, and so on down to three-hit elements.

The tree algorithm is very powerful since it looks for every possible track within the drift section using very fast processes. All of the slope cuts involve simple additions or subtractions to minimize the CPU time necessary to find an element.
The algorithm has been tested by applying it to randomly generated events with up to 15 tracks in the drift chamber. The algorithm is 100% efficient in finding every element with three or more hits, provided that the particle tracks are separated by more than one wire spacing. Figure 3.3 shows a DC2 hit pattern from an actual event containing a proton in the spectrometer. Shown in the figure is the hit pattern with both the left and right hits followed by the output element identified by the tree algorithm from the pattern. This figure is taken directly from the Quanah event display that allows the user to zoom in on a specific detector in order to check the performance of the algorithm in that detector.

A common problem with the tree algorithm is that it frequently finds too many elements associated with a cluster of hits. It finds elements that share the same hits where the number of these ambiguous elements, referred to as brothers, depends on the multiplicity of charged particles intersecting the drift chamber in the event, and also on the proximity of the track to the drift chamber wire. The problem of brothers is handled immediately after the elements with a specific number of hits are identified. But this is performed before the hits associated with them are removed from the list of hits, which is done in order to search for elements with fewer hits. All elements are assigned to groups of elements that share a common drift chamber hit. Each of these elements are then fit to a straight line using a least-squares method and their deviations from a straight line are recorded. The elements within a group are ranked according to their deviations. The element with the smallest deviation is given the highest rank. The user has the option to consider any number of elements in a group when forming the tracks, but this analysis only selects the best brother of each group.

Quanah must identify charge clusters corresponding to single charged particles intersecting the cathode pad planes of all three drift chambers from the list of pad hits and their ADC amplitudes. This task is complicated by the fact that each
Figure 3.3: Illustration of the tree algorithm operating on an actual E814 DC2 event. a) Recorded hit pattern along with all links formed by the tree algorithm. b) The element chosen by the tree algorithm as the best particle path.
Figure 3.4: Schematic diagram of the segmentation of the three E814 cathode pad detectors along with their respective dimensions.

Case 1:

Case 2:

Case 3:

Two unambiguous tracks present. Save both tracks.

Solution: Remove 4, OR remove 3 and 5.

Solution: Remove 6 and 9, OR remove 7 and 8.

Figure 3.5: Illustration of the operation of the cousin elimination algorithm.
of the pad planes have differing segmentation across the pad plane, as shown in Figure 3.4. The algorithm used to find pad clusters is to determine the total charge collected on the column of pads along each anode wire and compare the charge to a minimum threshold set at the expected amplitude of one minimum ionizing hit. If the sum is above the threshold, the algorithm then searches for the pad with the largest ADC value in that column and designates this as the centroid of the charge cluster. The algorithm next consults a map of the pad plane residing in memory. The map lists the pads that should be considered in order to find the total charge and the centroid of the cluster. The total charge of the cluster is determined by adding the ADC values of the pads in the list. The centroid along the wire is determined by calculating the centroid of the charge deposit using the list of pads in the list. The map is a simple look-up table that usually lists only the pads adjacent to the central pad. Using a look-up table and simple addition operations allows this portion of the pattern recognition to be very fast. A more detailed description of the performance of the pad cluster finding algorithm and the performance of the pad planes in general can be found elsewhere.18,36

Quanah also assigns the hits in the scintillator and calorimeter detectors of the spectrometer. Quanah converts calibrated relative positions of the hits in the scintillators and calorimeters into the global E814 coordinate system that has the target at its origin. Quanah uses the units of microns for this purpose in order to perform fast integer arithmetic throughout the pattern recognition process. The calibration of the scintillators and the calorimeters are described in detail elsewhere.16,26 The storage of the hits from these detectors are referred to as FSCI and UCAL clusters.

At this point, Quanah has identified track elements in DC2 and DC3, charge clusters in DC1, DC2, and DC3, and hit clusters in the FSCI and UCAL. The next
step in the pattern recognition process is to connect these constructs together to form track segments in the spectrometer downstream of the magnets.

Grouping the hits in the differing detectors into segments is performed by again using the tree algorithm that was applied to find the track elements in the drift chambers. The only difference is that each plane of wires in the drift chambers is replaced by a new construct called a pseudoplane. There are six pseudoplanes to be considered: one each for the DC2 wires, the DC2 pads, the DC3 wires, the DC3 pads, the FSCI, and the UCAL. The algorithm climbs through the hits on each pseudoplane in the same manner as for the wires, forming links between hits on adjacent pseudoplanes. The difference between this and the wire algorithm manifests itself in the manner in which two links sharing the same hit are compared. For example, when comparing links between the drift chamber pseudoplanes, the comparison is not only a slope cut as used for the wires, but, in addition, there is a constraint on the difference in the angles of the two drift chamber elements. When comparing a DC pseudoplane hit to an FSCI pseudoplane hit, the DC element must point towards the FSCI hit, within a specified tolerance. In this manner, the algorithm finds all possible straight line tracks within the spectrometer. The algorithm is designed so that the user can select the number of pseudoplanes to include in the track search along with which pseudoplanes to include in the search. Again there is a problem due to an overdetermination of track segments that share the same hit or hits. These are analogous to the brothers described earlier and are referred to as cousins. Cousins are ranked in groups in a similar manner as the brothers, again using the deviation of the hits from a straight line fit and storing the result as a segment quality factor.

Due to the high multiplicity of true particle tracks traversing the spectrometer, there is a high probability of identifying cousin tracks. This is not a significant problem for the data analysis presented here since there are at most
three true charged particle tracks in the spectrometer for the more central events considered. But, it is necessary to confront the problem of cousins for the analysis of the more peripheral events, which contain many more tracks in the spectrometer. This was accomplished by using a mathematical method that involves constructing what is called an *edge-inclusion table of the incompatibility graph* of the hits as outlined by S.R. Das. What the application of this method accomplishes is illustrated in Figure 3.5. By constructing the incompatibility graph and following the flowchart provided in the reference, it is possible to find an unambiguous group of track segments that are the most compatible with each other. When more than one group is possible, the groups are ranked according to quality factors assigned to each segment based on their straight line fits. Again, this analysis takes only the highest ranked grouping. Figure 3.6 shows the results of the cousin group selection algorithm on an actual event, taken from the Quanah event display, that contained four positively charged particles in the spectrometer. Figure 3.6a shows the event before selecting the cousins, where there are 18 segments found even though it is clear that there are only four particles traversing DC2 and DC3. The algorithm selected the four correct segments shown in Figure 3.6b.

With straight-line tracks identified downstream from the magnets, it is possible to project these tracks through the magnets to the target. These projections are performed assuming a uniform field model in both magnets where the magnetic fields in each magnet are assumed to extend three inches beyond the physical boundaries of the magnets in order to account for the fringe fields. This assumption was verified by measurement of the fringe magnetic fields, which decrease very sharply to zero at this point. If a segment successfully projects back to the target, it is stored as a track candidate.

The projection of each segment is first performed in the vertical direction, which is a straight line projection since there is no magnetic field bending the track.
in this direction. The vertical projection to the target uses the vertical position information from the DC2 and DC3 pads, if available, along with the FSCI. If the segment does not project to the target disk, then it is not saved as a track candidate. In the 1989 data taking period, the pad information was not available, so the FSCI position along with the assumption that the particle track originated at the E814 origin is used.

The equations used to project the segment to the target differ according to whether or not a DC1 pad cluster is present. If the DC1 cluster is absent, then there is not enough information in the segment to completely project it to the target, so the extra information is provided by assuming that the particle track originated at the E814 origin. With this assumption, the candidate magnetic rigidity is calculated. In this case, all segments are accepted as track candidates.

When the DC1 information is present, the projection algorithm begins by calculating the rigidity, again assuming that the track originated at the E814 origin as before. The algorithm continues by calculating where the candidate intersects DC1 in x and y. If there is a DC1 charge cluster within typically three pads of the projection, then its position is used to recalculate the segment rigidity and projection to the target. If the segment now does not project back to the target disk, then it is not accepted as a track candidate. If a DC1 cluster is not matched to the projection, then this analysis assumes that there is an inefficiency in the DC1 pad plane and accepts the segment as a candidate originating at the E814 origin.

After candidates have been identified, the pattern recognition process is complete. The resolutions of the angles of the particles from the target are $\Delta \Theta = 0.5$ mrad and $\Delta \Phi = 1.6$ mrad. The overall efficiency of Quanah is above 99% as determined from analysis of events containing a single 10 GeV/c proton provided by the AGS. Pattern recognition inefficiencies due to overlapping tracks are possible, but they are negligible in the data sample presented here since there is a
Figure 3.6: Illustration of the results of the cousin elimination routine on a real multiplicity 4 event. a) Event display showing all of the segments originally found by Quanah. b) The same event after applying the incompatibility graph algorithm.
Figure 3.7: Event displays showing the final results of the Quanah pattern recognition algorithm.  
(a) an event containing a proton and a negative pion. 
(b) an event containing a single proton. This is the typical event analyzed in this dissertation.
very low probability of events containing more than one nucleon in a given region of the detector. Figure 3.7 shows a pair of real event displays with an identified candidate. Figure 3.7b shows a typical event with a single proton in the spectrometer. Figure 3.7a shows a successfully identified proton and negative pion in the same event. This figure also shows the segmentation in each pad chamber. The pad planes have been folded down onto the page for viewing. The high multiplicity capabilities of Quanah are demonstrated in Figure 3.6, where four closely spaced charged particle tracks are identified.

### 3.3: PARTICLE IDENTIFICATION

Once a track candidate is identified, it is necessary to determine what type of particle is responsible for the track. The most commonly seen positively charged particles are pions, protons, and deuterons. This section describes how the particle identification is accomplished.

The pattern recognition procedure identifies tracks and assigns a magnetic rigidity, charge, time-of-flight, energy, theta angle, and phi angle in spherical coordinates to the track. From this information, it is necessary to calculate the interesting physics variables such as the rapidity, transverse momentum, and transverse mass of the identified track.

First, the relativistic velocity, \( \beta \), is calculated for each identified track, using the equation \( \beta = \frac{t_r}{t_c + t_a} \). Here \( t_r \) is the time-of-flight of a \( v = c \) particle calculated from the angles \( \theta \) (x-z plane) and \( \Phi \) (y-z plane) of the particle at the target. The time-of-flight of a \( v = c \) particle hitting the middle of the scintillator intersected by the identified track is \( t_c \). The actual time-of-flight measured by this scintillator (
with respect to a $v = c$ particle) is $t_x$. The relativistic quantity $\gamma$ can then be calculated from the value of $\beta$.

The components of the momentum of the track are calculated from the measured values of the longitudinal momentum and the angle of the track in the E814 coordinate system. The momentum parallel to the z-axis is determined by the equation $p_z = p \cdot \cos(\theta) \cos(\phi)$. The projection of the momentum along the x-axis is obtained using $p_x = p \cdot \sin(\theta) \cos(\phi)$. The projection of the momentum along the y-axis is obtained from $p_y = p \cdot \cos(\phi) \sin(\theta)$. The momentum perpendicular to the z-axis, or the transverse momentum, is determined by the formula $p_t = \sqrt{p_x^2 + p_y^2}$.

The calculation of the rapidity is performed by first identifying the particle using the variables calculated above as described below. Once this is done, the mass, $m$, of the particle is known and is used to calculate the rapidity. First, the energy of the particle is calculated assuming the particle mass with the equation $E_{\text{calc}} = \sqrt{m^2 + p^2}$. The rapidity is then calculated using the equation

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

Finally, the transverse mass is calculated using the equation

$$m_t = \frac{p_z}{\sinh(y)}.$$

Once tracks have been identified in the forward spectrometer along with their momenta and times-of-flight, it is possible to identify the particles associated with the singly charged tracks. The identification of protons is illustrated in Figure 3.8, obtained from the E814 closed geometry used in the 1989 data taking period. This figure shows the reciprocal of the momentum as measured by the drift chambers plotted against the time-of-flight as measured by the forward scintillators, with respect to a $v = c$ particle. The time-of-flight has been corrected for the differing flight path lengths to each scintillator. This plot shows singly charged particles only, therefore the momentum shown in the figure is identical to the
Figure 3.8: Particle identification plot for the closed geometry run. Mass lines of protons, deuterons, and pions are prominent. The box encloses particles tagged as protons.
Figure 3.9: Particle identification plot for the open geometry run. The box encloses particles identified as protons. Note the increased acceptance in momentum and time-of-flight compared to Figure 3.8.
magnetic rigidity. When plotted in this manner, the particles lie on several mass lines. This is due to the relationship $\beta = \frac{p}{\sqrt{p^2 + m^2}}$, since $\beta = \frac{v}{c}$ and $v = \frac{d}{(\text{time-of-flight})}$, where $d$ is the flight path length. In Figure 3.8, the mass lines for positive pions, protons, and deuterons are easily distinguishable. The events occurring within the box in the figure are those identified as protons. Figure 3.9 is the identical plot obtained from the E814 open geometry used in the 1991 data taking period. The larger range of time-of-flight and momentum are due to the smaller integrated magnetic field length present during this run.

At a pion momentum above about 7 GeV/c in the closed geometry run and 3 GeV/c in the open geometry run, it is no longer possible to separate the proton and pion mass lines. In this region, all pions are identified as protons. By extrapolating the pion yield into this region, it is determined that the pion contamination in the proton sample is only on the order of 1% near beam rapidity.

This dissertation concentrates on results of measurements of protons in the E814 apparatus. The spectrometer also has the ability to measure neutrons, primarily using the uranium calorimeters. It is instructive to compare the neutron measurements to the proton measurements in order to inspect the two data samples for any unexpected differences. The protons and neutrons are measured essentially independently, so comparing the two analyses is a useful check of the methods applied. To illustrate how this comparison is done, this section describes the neutron identification, which was performed using the cluster recognition designed by M. Fatyga\textsuperscript{25}, and analyzed by J. Stachel and R. Bellwied at SUNY - Stony Brook.

The neutrons are measured in six modules of the downstream UCAL array centered about the $z$-axis covering a total of 60 cm in the vertical direction and 63.2 cm in the horizontal direction. The strategy for identifying a neutron is to identify
an energy cluster in the UCAL modules with no corresponding hit present in the FSCI slat lying in front of the UCAL module. A detailed description of the energy cluster finding algorithm can be found elsewhere.\textsuperscript{25}

Kinematically, there should be no neutrons detected with a momentum greater than the beam momentum plus the neutron Fermi momentum, so cluster energies significantly greater than 20 GeV are considered to be due to two or more overlapping hits. In this case, the cluster-finding algorithm divides the cluster energy in half with a Gaussian width in energy to create two neutron hits. The width of this shared energy is determined by the calorimeter resolution. These overlapping hits occur on only about 2\% of the total neutron hits for central collisions. For peripheral collisions, this number rises to 13\% of the sample, but the shared energy is a good assumption since most neutrons should be near beam rapidity in this case.

The neutron identification algorithm returns the kinetic energy and the coordinates in x and y of the neutron hit at the calorimeter wall. The transverse momentum and rapidity is then calculated as described above for protons, only now assuming that the particle is a neutron. The transverse momentum resolution for the neutrons is dominated by the calorimeter energy resolution. For the largest $p_t$ at a given rapidity, the energy resolution contributes 10\% to the uncertainty in the transverse momentum measurement. In this respect, the proton measurement is more reliable since the uncertainties in the proton measurement are much smaller.

There is background present in the neutron sample from charged particles, photons, and secondary neutrons. The contamination due to charged particles is due to inefficiencies in the FSCI hodoscope, where the presence of a signal tags the particle as charged rather than neutral. The efficiency of a scintillator pulse height being present when a charged particle passes through it is 93\%, determined by comparing to the essentially 100\% efficient drift chambers.
The contamination due to photons, which are primarily due to pion decays, was determined by a Monte Carlo simulation that parameterized the pion distribution in AGS collisions using data from E802 and tracking them and their decays using the GEANT package described later. For the highest $E_t$ trigger, the photon contamination is estimated to be 20% for $y = 1.75$, 9% for $y = 2.0$, and 3% at $y = 2.5$. The background is lower for more peripheral collisions where fewer pions are produced. Also, contamination due to secondary neutrons should contribute less than 5% to the neutron sample.

3.4: DESCRIPTION OF THE DATA

All data were taken with a beam of $^{28}$Si at an energy of 14.6 Gev/A provided by the AGS. The beam is directed onto targets of $^{208}$Pb, $^{63}$Cu, and $^{27}$Al that were each 2% of a $^{28}$Si interaction length thick. Data were also taken with a 1% interaction length thick Pb target to measure target thickness effects. These targets were chosen to study relativistic heavy ion collisions for differing collision geometries. Si + Pb collisions of zero impact parameter correspond to full overlap of the two nuclei. For Si + Al collisions, zero impact parameter collisions are cases where not all of the Si nucleon trajectories intersect the Al nucleus. The Si + Cu collisions are intermediate between these two scenarios. The different targets also present differing thicknesses of nuclear material that the projectile nucleons must traverse in their collision trajectory for the most central collisions.

The number of incident beam particles for each target in 1989 was 426,628,427 on the Pb target; 437,847,660 on the Cu target; 260,934,091 on the Al target; and 580,383,623 on the empty target. For the 1991 period, there were 410,812,177 beam particles incident on the Pb target and 259,473,312 incident on the Al target. There were no data taken for the Cu target in 1991.
3.5: OFFLINE DATA CUTS

Even though the online trigger writes a very clean sample of events onto the data tapes, it is still necessary to scrutinize the events offline to ensure that they are not contaminated by events containing more than one beam particle or an interaction before the target. This section describes the offline cuts applied to the data set before track reconstruction is applied.

The first offline cut is a back-up for the "after-protection", or Level 1 trigger. This cut ensures that the beam scintillators located in the beam indeed register a pulse height consistent with a beam particle. If their pulse heights are close to twice that of a beam particle, the event is rejected as a double beam event. This occurs in less than 1% of the events.

An offline cut is also necessary to ensure that the beam does interact in the target. A cut of this type is needed due to inefficiencies in the pre-trigger. This is performed by examining the FSCI counter that is normally hit by the beam. If it is determined that a beam particle did hit this counter due to a pulse height consistent with that expected for a beam particle, then an interaction did not occur and the event is eliminated from the analysis. This occurs in less than 1% of the events written to tape.

Events that contain an interaction prior to the target must be vetoed offline. This cut compares the total energy deposited in the back wall of the TCAL with the total energy deposited in the side walls of the TCAL. If there is an excess of energy deposited in the back wall compared to the side walls, then an upstream interaction was most likely present and the event is rejected. The cut is defined by measuring the TCAL back wall to side wall correlation shown in Figure 3.10. Those events
outside of the gate shown are eliminated from the analysis as upstream interactions. Less than 5% of the events on tape are vetoed using this cut.

Another offline cut is implemented to ensure that the FERA trigger signal from the TCAL is consistent with the trigger level assigned to the event on tape. If the FERA signal is too small for the assigned trigger, the event is eliminated from the analysis. There is also a requirement on the correlation of the TCAL $E_t$ and the MULT charged particle multiplicity to veto downstream interactions at this point. This cut vetoes less than 1% of the events on tape.

Since the track reconstruction slows down considerably as the multiplicity of charged particles into the spectrometer increases, it is necessary to set a cut on the centrality of the collision before reconstructing tracks. The additional centrality cut is performed offline by requiring that an event have a minimum $E_t$ measured by the TCAL associated with it. The minimum $E_t$ is set at 5 GeV for Si + Pb collisions, 3 GeV for Si + Cu collisions, and 1 GeV for Si + Al collisions. The cut is designed only to facilitate the available computer resources for the analysis and does not reflect any limitation other than CPU time used by the track reconstruction program.

A final cut is necessary due to a failure in the FASTBUS CAT (Calibration And Testing) card electronics during the closed geometry run. This electronics problem manifested itself by failing to transmit the DC2 information for the recorded event. The exact number of events this occurred for is determined and included as a detector inefficiency in the cross section calculations presented later. This is done offline by reading the error word written to tape from the CAT card of the TDC FASTBUS crate. If the error word indicates that there is a failure in the CAT card, the event is rejected and tallied. The efficiencies of the CAT card electronics during the closed geometry run are 85.17% for Si + Pb data, 84.06% for Si + Cu data, and 82.85% for Si + Al data. All cross sections from the closed
geometry analysis have been corrected for this inefficiency. This electronics problem was solved before the 1990 and open geometry runs and this cut became unnecessary.
Figure 3.10: Plot of the $E_t$ deposited in the back wall of the TCAL vs. the $E_t$ deposited in the side walls of the TCAL. The events outside of the gate are due to upstream interactions, which deposit substantial energy in the back wall, and are eliminated from the analysis.
CHAPTER 4: RESULTS

Previously, the E814 apparatus has been discussed along with the data analysis method applied to identify particles and measure their momenta and rapidity. Chapter 4 will present the results of the measurements of protons, neutrons, deuterons, and pineuts in the forward spectrometer. Most of the results will be presented as functions of the event centrality as measured by the TCAL. The interpretation of the results will be done in Chapter 5.

4.1: ACCEPTANCE CORRECTIONS

An important consideration in obtaining production and interaction cross sections is the experimental acceptance for detecting a particle of a particular type. The following question must be answered: Given a particle with rapidity, \( y \), and transverse momentum, \( p_t \), is it kinematically possible for its trajectory to traverse the spectrometer detectors? The answer should include a consideration of the geometrical arrangement of the detectors and the physics effects such as multiple scattering in the detector materials. This section describes how the geometrical acceptance of the spectrometer is calculated for protons, neutrons, and deuterons. The acceptance is calculated in the form of correction factors, which are the reciprocals of the geometrical efficiency for accepting a particle in the apparatus. The pineut acceptance will be discussed later.

The determination of the corrections to apply to the data due to the geometrical acceptance of the E814 detectors, is done by computer simulation using the GEANT package, version 3.1305. GEANT is ideally suited for acceptance studies of an experimental apparatus since it has the ability to calculate the
Figure 4.1: The E814 apparatus as described in the GEANT simulation program.
trajectory of user-specified particles from the target to the detectors of the experiment. GEANT also includes a graphics package that allows the user to view a two-dimensional projection of the experiment and any particle trajectories going through the apparatus. Figure 4.1 shows the GEANT view of the E814 apparatus for the 1989 run. The corrections are obtained including the concrete shielding blocks, which partially block the path of protons to the right-most downstream FSCI scintillators.

GEANT allows the user to specify the geometrical dimensions and position of each detector within the experimental setup by first defining a master volume, typically in the shape of a rectangular box, in which the other detectors, referred to as volumes within the GEANT framework, are placed. GEANT allows the definition of the type of material that each detector is made of. This is used by the program to account for, for example, multiple scattering effects of the particle trajectory through the detector material. The user has the option of defining each detector as sensitive or insensitive. Sensitive detectors are those that provide measurements of the particle trajectory. GEANT will record variables such as the position, momentum, energy, and time-of-flight of the particle in a sensitive detector. This information is not recorded when the particle traverses an insensitive detector, but multiple scattering and other interaction processes are still taken into account in these volumes. Once each of the detector volumes are defined and positioned, GEANT allows the user to generate particles, such as protons or neutrons, with an initial transverse momentum, rapidity, and position. The particle trajectory is then tracked through the apparatus in small steps until it comes to rest in one of the detector volumes or escapes the master volume. If a particle decays as it traverses the apparatus, GEANT continues to track the decay products. GEANT also tracks the particles through any magnetic fields present.
GEANT is used to generate acceptance correction factors for both protons and neutrons using the procedure described below. A random transverse momentum of the nucleon is generated uniformly from 0.0 to 0.5 GeV/c. Also, a random rapidity of the nucleon is generated uniformly from 0.0 to 5.0. GEANT requires the initial four momentum of the particle as input before it can proceed to track the nucleon through the apparatus. Therefore, a random angle, theta, is generated uniformly from -180 to + 180 degrees, which is then used to determine the projections for the x and y components of the momentum, p_x and p_y. The z component of the momentum, p_z, is determined from the rapidity using the equation

\[ p_z = m_t \sinh(y), \]

where \( m_t = \sqrt{p_t^2 + m_0^2} \). The origin of the proton trajectory is generated uniformly over the width of the AGS beam spot size centered at the origin of the E814 coordinate system. Once the initial coordinates and momenta are defined, a counter corresponding to the bin in which the generated y and p_t lie is incremented by one to count the number of particles generated for tracking through the apparatus.

To generate the acceptance corrections, only the upstream and downstream FSCI scintillators are defined as sensitive detectors in GEANT. The drift chambers can be defined as insensitive volumes since any particle hitting the scintillators also traverse the drift chambers. Only generated nucleons intersecting the FSCI scintillators are counted as accepted particles. When this occurs, GEANT tells the user that there is a valid detector hit in this event, and a new counter is incremented corresponding to the bin in initial y and p_t of the generated nucleon. In order to determine the acceptance correction factor of a specific y and p_t bin, it is only necessary to take the ratio of the accepted nucleon counter for that bin to the generated nucleon counter, yielding the efficiency for accepting a nucleon with that initial y and p_t. A total of 50000 events were tracked to produce the correction.
factors applied to the data shown here. For all closed geometry (1989 run) data, if a specific bin in rapidity or $p_t$ has a correction factor greater than 5.0 corresponding to it, the correction factor is reset to 0.0. There must be at least 20% acceptance in a rapidity or $p_t$ bin in order for that bin to be presented in the acceptance corrected data shown here. For the open geometry (1991 run) data, the correction factors are allowed to reach as high as 10.0, or 10% geometrical efficiency due to the high statistics of this run. The correction factors (the inverse of the acceptance efficiency) for both geometry runs are shown in Figures 4.2 and 4.3 for different $p_t$ bins as functions of rapidity.

It was discovered that there was a small tilt to the incident angle of the beam of 0.048 degrees in the magnetic field bend direction during both running periods, which was taken into account in the acceptance corrections by adjusting the generated proton momentum by this angle before allowing GEANT to track the particle. Also, during both running periods, the two FSCI scintillators normally hit by the beam were only about 70% efficient for detecting charged particles. To properly account for the inefficiencies, these FSCI scintillators, numbered 38 and 39, were excluded from the proton data analysis. This exclusion was taken into account by defining these scintillators as insensitive detectors in the GEANT program when obtaining the acceptance correction factors.

In order to apply the geometrical acceptance correction factors to the data, it is necessary to ensure that the data and the correction factors have the same bin widths in $y$ and $p_t$. Then it is a simple matter of multiplying the data by the correction factors bin-by-bin to obtain the acceptance corrected spectra.

Figure 4.4a plots the observed acceptance for protons in the spectrometer for the closed geometry run as the measured rapidity versus the transverse momentum. Protons that lie to the right of the line shown are those that can be measured in the
Figure 4.2: Acceptance correction factors for the closed geometry spectrometer as a function of $p_t$ for rapidity intervals 0.2 units wide. Any correction factor greater than 5.0 is considered outside of the acceptance.
Figure 4.3: Acceptance correction factors for the open geometry spectrometer as a function of $p_t$ for rapidity intervals 0.2 units wide. Any correction factor greater than 10.0 is considered outside of the acceptance.
Figure 4.4: a) Acceptance in $p_t$ and $y$ for protons and neutrons (solid and dashed lines, respectively) for the closed geometry spectrometer. The solid line with dots marks the $p_t$ values where the acceptance drops below 100% for protons. b) Acceptance correction factors for three selected rapidity bins, indicated as hatched areas in (a), as a function of $p_t$ for protons.
Figure 4.5: Measured acceptance in $p_t$ and $y$ for protons in the open geometry spectrometer.
Figure 4.6: Comparison of the acceptances in $p_t$ and $y$ for protons in three AGS experiments: the E814 open and closed geometry spectrometer and the E802 spectrometer.
forward spectrometer. Also shown is the boundary line for the measured acceptance of neutrons in the spectrometer.

In order to better appreciate the closed geometry proton acceptance, Figure 4.4b shows the reciprocal of the geometrical efficiency for accepting a proton in the forward spectrometer as a function of transverse momentum. This plot is generated from Figure 4.4a for three rapidity bins by projecting the values for the geometrical efficiency onto the transverse momentum axis. The upper-most line in this plot illustrates the full detection efficiency reaching greater than 300 MeV/c in $p_t$ at beam rapidity. The acceptance in $p_t$ falls drastically for rapidities less than beam rapidity to less than 100 Mev/c near $y = 2.0$. On account of this limited acceptance at low rapidities, results from the closed geometry run will primarily concentrate on the properties of the beam rapidity particles.

Figure 4.5 shows the measured acceptance for protons during the open geometry run. The acceptance in $p_t$ is much improved since the PCAL has been removed, making the opening into the spectrometer much larger since it is now provided by the magnet opening. Also, the open geometry spectrometer uses only one analyzing magnet with a 4.22 Tesla magnetic field as opposed to the two analyzing magnets with 4.18 Tesla fields each in the closed geometry spectrometer. The increased $p_t$ acceptance near $y = 2.0$ now extends to 250 Mev/c, as shown in Figure 4.3. This increased acceptance allows for more detailed study of the lower rapidity particles. The difference in geometrical acceptance for protons in the two running periods is illustrated in Figure 4.6, which overlays the two acceptances in rapidity and $p_t$ space. Both running periods have full acceptance for beam rapidity protons, but the open geometry acceptance covers a broader range of $p_t$, slightly overlapping the acceptance of another AGS experiment, E802, which also has a spectrometer capable of measuring protons in heavy ion collisions. The increased
RESULTS: ACCEPTANCE CORRECTIONS

$p_t$ acceptance of the open geometry run better facilitates comparisons between the complementary E814 and E802 experiments.

4.2: NUCLEON SPECTRA

This section will present the results of measurements made on protons detected in the forward spectrometer acceptance from both the closed and open geometry runs and will demonstrate that there are two distinct components in the proton rapidity spectra. This section will also address the nature of the processes producing the proton components.

As discussed in the introduction, it is instructive to measure the longitudinal dimension of the reaction dynamics by examining the rapidity of the resultants of the reaction as a function of the event centrality. Figure 4.7 shows the proton rapidity spectra selecting the three different TCAL $E_t$ trigger levels for Si + Pb collisions. The three TCAL triggers correspond to interaction cross sections of 593 mb, 102 mb, and 6.9 mb for the low $E_t$, middle $E_t$, and high $E_t$ triggers, respectively. The spectra shown are of protons detected in the spectrometer. The data have not been corrected for the geometrical acceptance.

In each spectrum, it is clear that there are two distinct components in the proton rapidity distributions. There is a component peaked at beam rapidity ($y = 3.44$) and a component of protons at lower rapidity. The width of the beam rapidity proton peak is 0.3 units in rapidity (full-width-half-maximum), corresponding to 4.4 GeV/c, or 30% in momentum. This is much larger than the momentum resolution of the drift chambers, which is better than $\sigma_y = 0.002$ at this magnetic field setting. The width of the beam rapidity peak is due to the fermi momentum of the protons.
Figure 4.7: Rapidity cross sections of protons measured in the closed geometry spectrometer for Si + Pb collisions plotted for the three TCAL $E_t$ triggers. The dashed lines are fits to the Goldhaber fragmentation model using a fermi momentum of 270 MeV/c.
Figure 4.8a: Rapidity cross sections of protons measured in the closed geometry spectrometer for Si + Cu collisions divided into the three TCAL $E_t$ triggers.
RESULTS: NUCLEON SPECTRA

14.8 Gev/nucleon $^{28}$Si + $^{27}$Al - Protons

Figure 4.8b: Rapidity cross sections of protons measured in the closed geometry spectrometer for Si + Al collisions divided into the three TCAL $E_t$ triggers.
Figure 4.9: Rapidity cross sections of neutrons measured in the closed geometry spectrometer for Si + Pb collisions divided into the three TCAL $E_T$ triggers. The dashed line in the top plot is a fit to the Goldhaber fragmentation model using a fermi momentum of 270 MeV/c. The solid line in the bottom plot is the Landau fireball model prediction. The dots in the bottom curve are the HIJET with rescattering prediction.
and will be discussed in more detail in Chapter 5. The fall-off in the distribution of the lower rapidity protons is caused by the decreasing acceptance of the spectrometer at these rapidities rather than a decrease in the proton yield.

From Figure 4.7, it is apparent that the ratio of the number of protons in the beam rapidity component to the number of lower rapidity protons decreases as the centrality of the events increase. This is an indication that as the impact parameter decreases, less protons survive the event without interacting. Also, the absolute magnitude of the number of protons entering the spectrometer decreases as the centrality increases, indicating that fewer protons make it to the spectrometer when the impact parameter is smaller. This is a first indication of the lack of transparency in these reactions and will be explored quantitatively later.

Data for the Cu and Al targets are shown in Figure 4.8. The rapidity distributions for these targets are identical in shape to the low $E_t$ Si + Pb spectra for all three levels of $E_t$ since those triggers cover a very small range of impact parameter compared to the Pb triggers. A significant peak in the proton rapidity spectra remains at all transverse energies for these targets. This will be discussed in more detail later. The corresponding spectra for neutron data analyzed by the SUNY - Stony Brook group in the E814 collaboration, are shown in Figure 4.9 for the same three TCAL $E_t$ triggers over slightly different $E_t$ ranges from the 1988 run. The beam rapidity peak of the neutrons is wider than that for protons due to the poor energy resolution of the UCAL detectors. The uncertainties shown in this plot are statistical. The plotted curves will be discussed in Chapter 5.

The rapidity distributions discussed above measure the distribution of nucleons after the collision in the longitudinal direction only. The behavior of the nucleons in the transverse direction can be explored by measuring their transverse
Figure 4.10: Transverse momentum cross sections of $y > 3.2$ protons measured in the closed geometry spectrometer for Si + Pb, Cu, and Al collisions from the middle TCAL trigger. The dip in the spectra is due to the FSCI inefficiency.
Figure 4.11: Transverse momentum cross sections of $y > 3$ neutrons measured in the closed geometry spectrometer for Si + Pb, Cu, and Al collisions from the middle TCAL trigger. The bottom panel shows the acceptance correction factors over this $p_t$ range. The dashed line is a fit to the Goldhaber fragmentation model using a fermi momentum of 270 MeV/c.
Figure 4.12: Transverse momentum distribution of $y > 3.2$ protons in the open geometry spectrometer from $\text{Si} + \text{Pb}$ collisions. The curves are the scaled distributions from all three TCAL triggers.

14.6 GeV/A $^{28}\text{Si} + ^{208}\text{Pb}$ – Protons $y > 3.2$

- - - - - - HIGH Multiplicity Trigger $\times 2.5$
- - - - - - - MID Multiplicity Trigger $\times 1.7$
- - - - - - - - - - - - - - LOW Multiplicity Trigger

Goldhaber fit $p_t = 270$ MeV/c

Beam FSCI Inefficiency

Figure 4.12: Transverse momentum distribution of $y > 3.2$ protons in the open geometry spectrometer from $\text{Si} + \text{Pb}$ collisions. The curves are the scaled distributions from all three TCAL triggers.
Figure 4.13a: Invariant cross sections times 2π for protons in rapidity intervals 0.2 units wide for Si + Pb collisions and the middle TCAL trigger. The bottom curves correspond to $y = 2.0-2.2$ and increase in 0.2 $y$ unit steps. The distributions are multiplied by successive factors of 5 for clarity.
Figure 4.13b: Invariant cross sections times 2π for neutrons in rapidity intervals 0.2 units wide for Si + Pb collisions and the middle TCAL trigger. The bottom curves correspond to y = 2.0-2.2 and increase in 0.2 y unit steps. The distributions are multiplied by successive factors of 5 for clarity. The dashed, solid, and long dashed lines are fits to Boltzmann distributions with temperatures of 150, 10, and 5 MeV, respectively.
Figure 4.14a: Invariant cross sections times 2π for protons in rapidity intervals 0.2 units wide for Si + Cu collisions and the middle TCAL trigger. The bottom curves correspond to y = 2.0-2.2 and increase in 0.2 y unit steps. The distributions are multiplied by successive factors of 5 for clarity.
Figure 4.14b: Invariant cross sections times $2\pi$ for protons in rapidity intervals 0.2 units wide for Si + Al collisions and the middle TCAL trigger. The bottom curves correspond to $y = 2.0-2.2$ and increase in 0.2 $y$ unit steps. The distributions are multiplied by successive factors of 5 for clarity.
momentum. Figure 4.10 shows the transverse momentum of beam rapidity protons \( y > 3.2 \) entering the spectrometer for Si + Pb, Cu, and Al collisions for the middle \( E_t \) trigger during the closed geometry run. A similar plot is shown in Figure 4.11 for neutrons from the 1988 data taking period. Below the neutron plot is the reciprocal of the geometrical efficiency of finding the neutron in the spectrometer. To obtain the acceptance corrected spectra, multiply the \( p_t \) distribution by the efficiency curve bin by bin. For beam rapidity nucleons, the acceptance does not change the spectra except for transverse momenta above about 200 MeV/c. Figure 4.12 shows the transverse momentum for beam rapidity protons detected in the spectrometer during the open geometry run. The spectra taken for all three multiplicity trigger levels are scaled and overlayed to demonstrate that the shape of the beam rapidity nucleon \( p_t \) spectrum does not change with event centrality, suggesting that the beam rapidity nucleons are products of processes that are independent of the impact parameter, which would be the case if the beam rapidity nucleon component were due to those that do not interact in the collision. A detailed analysis of this type is performed elsewhere.49

The differences in the beam rapidity nucleon component and the lower rapidity nucleon component can be further investigated by studying the transverse momentum distributions more carefully. This is accomplished by dividing the \( p_t \) distributions into rapidity bins of width 0.2 units of rapidity and selecting only the middle \( E_t \) trigger for maximum statistics. The high \( E_t \) trigger gives similar results since it covers a similar range of impact parameters. The binned \( p_t \) distributions for protons and neutrons are then plotted as invariant cross sections as shown in Figure 4.13. Here, the vertical axis for the proton distribution \( 2\pi\sigma_{inv} = \frac{1}{p_t} \frac{d^2\sigma}{dp_t dy} \). The bottom-most curve covers the rapidity \( y = 2.0 - 2.2 \) and the top curve covers rapidity \( y = 3.4 - 3.6 \) with the curves in between covering successive steps of 0.2 units of
RESULTS: NUCLEON SPECTRA

rapidity. Since these distributions visually lie on top of each other, they have been multiplied by successive multiples of five in order to separate them on the plot. These spectra have been corrected for acceptance bin-by-bin in \( p_t \) using the procedure described earlier. Typical statistical uncertainties are shown on this plot. Figure 4.14 shows similar plots taken for Si + Cu and Si + Al collisions.

From the closed geometry data, the range of transverse momentum covered by each rapidity bin is too small to extract a reliable exponential slope of the curve. This must be performed in order to extract a Boltzmann temperature parameter associated with each rapidity interval, assuming that the system is thermalized. Instead of extracting a slope in this case, it is still possible to obtain a reliable intercept of each curve at \( p_t = 0 \). The intercept is determined by fitting each curve to an exponential curve (Boltzmann distribution) in \( p_t \) to a function of the form

\[
f(p_t) = C e^{-\frac{p_t}{T}}
\]

where \( C \) is a constant and \( T \) is the inverse slope parameter (Boltzmann temperature). The intercept of the fit at \( p_t = 0 \) is extracted for each rapidity bin. This is done for all three targets (Pb, Cu, and Al) and for both protons and neutrons. In order to compare the different targets, each curve was divided by the middle \( E_t \) trigger cross section for each target so that each curve corresponds to a sampling of 4% of the geometrical cross section, yielding values corresponding to the rapidity densities of the protons and neutrons at \( p_t = 0 \). The results of this analysis are shown in Figure 4.15. Identical results are obtained from the open geometry data for protons fitting to the increased \( p_t \) range. The points connected by the solid lines (to guide the eye) are for protons, while the neutron points are connected by dashed lines. The statistical errors for these data points are roughly the size of the data points shown. In order to determine a systematic error due to the functional fit and the \( p_t \) range included in the fit, the fit parameters were varied, yielding systematic errors of about 10 - 15% on the intercepts.
Figure 4.15: Rapidity density at $p_t = 0$ for protons and neutrons from Si + Pb, Cu, and Al collisions. For clarity, the neutron points are displayed 0.02 $y$ units above the center of each rapidity interval, and protons 0.02 $y$ units below. The data points are connected to guide the eye.
There is a clear peak in the intercept spectrum of Figure 4.15 for nucleons with rapidity above $y = 3$, again demonstrating a marked difference in the nucleons at beam rapidity and those at lower rapidities. The beam rapidity peak for protons is narrower than that for neutrons due to the improved resolution for the proton measurement. For the Pb target, there is a clear excess of neutrons over protons in Figure 4.15 by a factor of $4/3 = 1.33$, reflecting the neutron to proton ratio in the Si + Pb overlapping participant volume of $63/46 = 1.37$.

Since the closed geometry data does not provide adequate transverse momentum coverage for the extraction of slope parameters from the $p_t$ spectra, it is desirable to increase the $p_t$ coverage. This was accomplished in the open geometry running period with data collection taken for various magnet settings using magnetic field polarities that bend positively charged particles in both the negative and positive $x$ directions. Shown here are data only for the 4.2 Tesla positive polarity running period. Data taken using a 2.1 Tesla positive polarity magnetic field setting further increased the $p_t$ coverage. All data presented here agrees with the preliminary results from the lower field.35

With enough $p_t$ coverage to extract a slope parameter from the proton $p_t$ spectra, it is best to plot the transverse momentum in the form of transverse mass, $m_t$. This can also be plotted in terms of the transverse kinetic energy, or $T_t = (m_t - m_0)$, which has the advantage of orienting the lowest $p_t$ values at $T_t = 0$, making the plot easy to read as opposed to $m_t$ plots where the lowest $p_t$ values are oriented at $m_t = m_0$. The nucleon invariant cross section, $E \frac{d^3\sigma}{d^3p}$ in the form

$$\frac{1}{2\pi m_t^2} \frac{d^2N}{dy \cdot dm_t},$$

where $N$ is the number of protons emitted into that $m_t$ and $y$ bin per event. By plotting the invariant cross section as a function of the transverse...
mass and fitting the spectra to a function of the form \( f(m_t) = Ce^{-m_t/T_B} \), where \( C \) is a constant, the Boltzmann temperature, \( T_B \), is determined.

The transverse mass for protons have been plotted in rapidity bins starting at \( y = 2.6 \) and going up to \( y = 3.8 \) in steps of 0.2 rapidity units, as shown in Figure 4.16 for Si + Pb collisions selecting the middle \( E_t \) trigger. The data points shown are plotted with statistical uncertainties. Some points at lower \( p_t \) values are missing from the \( T_t \) plots. These are areas where the correction factors for those \( p_t \) bins exceed 10.0 due to the inefficiencies in the forward scintillators hit by the beam. These points are excluded from the fit. The straight lines shown are the fits to the function \( f(m_t) = Ce^{-m_t/T_B} \) where \( T_B \) is the slope parameter that corresponds to the temperature of this Boltzmann distribution. Table 4.1 lists the slopes and constants along with their fit errors for each rapidity bin shown in Figure 4.16.

Assuming that a thermal system of hot matter is created in relativistic heavy ion collisions at AGS energies, a Boltzmann distribution of the transverse momentum is expected to be measured for protons. The Boltzmann temperature parameters are plotted in Figure 4.17 as a function of rapidity. The temperature parameters start at about 60 MeV for the beam rapidity protons and rise to above 150 MeV as the plot approaches mid-rapidity. At \( y = 2.6 \), the acceptance in \( p_t \) becomes insufficient for further extraction of slopes from the \( m_t \) plots. This data has been extended in further preliminary analyses. In the \( m_t \) spectra for \( y > 3 \), there is evidence of a steeper component at low \( m_t \). This effect is difficult to see in Figure 4.16 due to the FSCI acceptance, but it is a real effect as evidenced by the measurements at the lower magnetic fields.35 The low \( m_t \) portion of the beam rapidity proton spectra has a steeper slope corresponding to a much smaller temperature parameter, and is attributed to the protons that do not interact in the collision.
Figure 4.16: Transverse mass distributions for protons from Si + Pb collisions and the middle TCAL trigger divided into rapidity intervals 0.2 units wide. The solid lines are Boltzmann distribution fits to the spectra.
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Proton Inverse Slope Parameters

Figure 4.17: Boltzmann temperature parameters as a function of rapidity for Si + Pb collisions and the middle multiplicity trigger.

Figure 4.18: dN/dy distribution for Si + Pb collisions and the middle multiplicity trigger.
A goal of the proton analysis is to determine where all of the protons have gone in rapidity since the beginning of the collision to determine the extent of the interaction process during the collision. Before the collision, all of the projectile protons are clustered near beam rapidity as constituents of the incident nucleus. As the collision proceeds, most of the protons in a central collision will undergo interactions and become shifted down in rapidity by some amount below the original beam rapidity. The more protons seen shifting to lower rapidities, the more energy is being deposited in the system. A plot of the proton rapidity density, \( dN/dy \), illustrates where the protons lie in rapidity after the collision. The integral of a \( dN/dy \) plot over the full rapidity range should be the total number of protons in the projectile-target system.

<table>
<thead>
<tr>
<th>Rapidity</th>
<th>( m_t = m_0 ) constant</th>
<th>( T_B )</th>
<th>( T_B ) error</th>
<th>( dN/dy )</th>
<th>( dN/dy ) error</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.4-3.6</td>
<td>16.8</td>
<td>61 MeV</td>
<td>4.8 MeV</td>
<td>0.244</td>
<td>0.184</td>
</tr>
<tr>
<td>3.2-3.4</td>
<td>11.7</td>
<td>98 MeV</td>
<td>5.1 MeV</td>
<td>0.686</td>
<td>0.296</td>
</tr>
<tr>
<td>3.0-3.2</td>
<td>10.7</td>
<td>117 MeV</td>
<td>2.1 MeV</td>
<td>1.521</td>
<td>0.236</td>
</tr>
<tr>
<td>2.8-3.0</td>
<td>9.1</td>
<td>150 MeV</td>
<td>3.5 MeV</td>
<td>2.550</td>
<td>0.454</td>
</tr>
<tr>
<td>2.6-2.8</td>
<td>8.7</td>
<td>173 MeV</td>
<td>4.3 MeV</td>
<td>4.325</td>
<td>0.700</td>
</tr>
</tbody>
</table>

Table 4.1: Numerical values for the intercepts and inverse slope parameters (Boltzmann temperature \( T_B \)) measured to obtain \( dN/dy \) for Si + Pb collisions. These values are plotted in Figures 4.17 and 4.18.

The \( dN/dy \) plot is obtained from the transverse mass distribution shown in Figure 4.16. This is done for each rapidity bin by integrating the plot from \( T_t = 0 \) to infinity by using the constant and slope parameter extracted from the exponential fit, assuming that the Boltzmann distribution holds to infinite \( p_t \). The steep
component of the spectra at low $m_t$ is neglected in the $dN/dy$ extrapolation. The resulting $dN/dy$ plot for Si + Pb collisions is shown in Figure 4.18 as a function of rapidity selecting the middle multiplicity trigger from the open geometry run. This plot shows that at beam rapidity, $y=3.44$, there are less than 0.1 protons in an event still at beam rapidity. The low value of this number suggests a very low degree of transparency in heavy ion collisions at this energy. This will be discussed in more detail in the next section. Low transparency is also implied by the fact that there is not a peak in $dN/dy$ at beam rapidity (or target rapidity either in the Si + Al case shown in Figure 4.21). For Si + Pb, at $y=2.7$, there are 4.3 protons falling into that rapidity bin, therefore almost all of the protons undergo an interaction in the more central collisions.

<table>
<thead>
<tr>
<th>rapidity</th>
<th>$m_t - m_0$ constant</th>
<th>constant error</th>
<th>$T_B$ (MeV)</th>
<th>$T_B$ error (MeV)</th>
<th>$dN/dy$</th>
<th>$dN/dy$ error</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.4-3.6</td>
<td>22.2</td>
<td>0.17</td>
<td>51 MeV</td>
<td>5.0 MeV</td>
<td>2.30</td>
<td>0.54</td>
</tr>
<tr>
<td>3.2-3.4</td>
<td>15.9</td>
<td>0.16</td>
<td>80 MeV</td>
<td>10.2 MeV</td>
<td>5.22</td>
<td>1.52</td>
</tr>
<tr>
<td>3.0-3.2</td>
<td>13.1</td>
<td>0.14</td>
<td>104 MeV</td>
<td>14.7 MeV</td>
<td>6.26</td>
<td>0.84</td>
</tr>
<tr>
<td>2.8-3.0</td>
<td>11.3</td>
<td>0.05</td>
<td>129 MeV</td>
<td>9.5 MeV</td>
<td>6.87</td>
<td>1.67</td>
</tr>
<tr>
<td>2.6-2.8</td>
<td>11.0</td>
<td>0.05</td>
<td>137 MeV</td>
<td>11.5 MeV</td>
<td>9.19</td>
<td>2.06</td>
</tr>
</tbody>
</table>

Table 4.2: Numerical values for the constants and inverse slope parameters ($Boltzmann temperature T_B$) measured to obtain $dN/dy$ for Si + Al collisions. These values are plotted in Figures 4.20 and 4.21.

An identical analysis to that described above was performed on data from Si + Al collisions in order to extract the rapidity distribution. The transverse mass plots in rapidity intervals 0.2 rapidity units wide near beam rapidity are shown in Figure 4.19 along with the Boltzmann distribution fit to each spectra. Again, these plots suffer from the scintillator inefficiencies, and the affected data points are not
Figure 4.19: Transverse mass distributions for protons from Si + Al collisions and the middle TCAL trigger divided into rapidity intervals 0.2 units wide. The solid lines are Boltzmann distribution fits to the spectra.
Figure 4.20: Boltzmann temperature parameters as a function of rapidity for Si + Al collisions.

Figure 4.21: dN/dy distribution for Si + Al collisions. The plot has been reflected about mid-rapidity since this is very nearly a symmetric system. The integral of the curve from a smooth extrapolation at mid-rapidity is 28.4 ± 3.1, the number of protons in the system within errors.
Figure 4.22: Mean multiplicity per event of beam rapidity nucleons for Si + Pb, Cu, and Al collisions. Solid and open symbols correspond to protons and neutrons, respectively.
included in the fits. The Boltzmann temperature parameters thus obtained are shown in Figure 4.20 to be similar to those extracted for Si + Pb collisions. The dN/dy plot for Si + Al collisions is shown in Figure 4.21 and the values of the fits and their errors used to extract dN/dy are listed in Table 4.2. Since the Si + Al system is very nearly symmetric, it is possible to reflect the rapidity curve about mid-rapidity in order to obtain the target rapidity distribution. This reflection is also shown in Figure 4.21.

It has been established throughout this chapter that there is a distinct difference in the mechanisms involving the beam rapidity protons at y > 3.2 and those at lower rapidities. Much can be learned by simply counting the number of beam rapidity protons as a function of the centrality of the collision, or as a function of the transverse energy measured by the TCAL. This number can be expressed as a mean multiplicity per event, <M>, of protons as a function of E_t. Figure 4.22 displays this dependence for beam rapidity protons (y > 3.2) and for beam rapidity neutrons (y > 3) for Si + Al, Si + Cu, and Si + Pb collisions. The mean geometrical acceptance for both beam rapidity protons and neutrons in the forward spectrometer is 71%.

The mean multiplicity per event decreases rapidly with increasing target mass. For each target, the highest point in E_t easily corresponds to full overlap of the projectile and target nuclei. The values of <M> for the most central collisions give an indication of the transparency of each target. Obviously, more transparency in a central collision will yield more beam rapidity nucleons surviving the collision. The low values of <M> for each target give an indication of the low degree of transparency present in heavy ion collisions at these energies. These results will be presented in a more quantitative manner in the next chapter.

Particularly for the Pb target, the value of <M> decreases with increasing centrality. This trend is very pronounced in the Pb target since the E_t values cover a
wide range of impact parameters. The low $E_t$ end of this curve corresponds to 20% of the geometrical cross section for Pb while the high $E_t$ end corresponds to only 0.002% of the geometrical cross section. A decrease in $<M>$ of about a factor of 20 is observed over this range. In particular, for $E_t = 6.0$ Gev, only about one proton and one neutron per event survive the collision with beam rapidity. Increasing the $E_t$ to 16 Gev decreases the number of surviving protons and neutrons to about 0.03 per event. This magnitude of decrease is not apparent in the Cu and Al targets since the $E_t$ range covered in this plot for these detectors correspond to a small range of impact parameters that essentially correspond to full overlap of the projectile and target nuclei.

The excellent agreement between the proton and neutron measurements of $<M>$ is striking, considering that these are independent measurements. The neutron measurement is performed primarily using the calorimeter energy information while the proton measurement is performed using the drift chambers momentum and forward scintillator charge and time-of-flight information.

4.3: DEUTERON SPECTRA

This chapter has thus far been concerned with data using the nucleon as a probe of the nuclear collision system. This section will present results of measurements of beam rapidity deuterons in the E814 forward spectrometer. Using the deuteron as a probe of the system is interesting for two reasons. First, the deuteron is a larger object than the proton or neutron with a larger reaction cross section with the nucleons in the target nucleus. Measuring the mean multiplicity of beam rapidity deuterons can be a useful check of the interpretation of the nucleon results. Also, the deuteron is a complex system consisting of a weakly bound proton
and neutron. It does not take much energy (the deuteron binding energy is 2.23 MeV) to separate the constituent proton and neutron. If there is excess energy available in the collision, a smaller number of beam rapidity deuterons are expected to be measured since the available energy in the system can overcome the binding energy of some of the deuterons, resulting in fewer final state deuterons. But, a measurement of this type can be affected by final state interactions (such as coalescence) and impact parameter fluctuations that could increase the number of beam-rapidity deuterons detected.

This deuteron analysis will concentrate only on the beam rapidity component of the deuteron sample. Lower rapidities have been studied by experiment E8028 and are currently being studied in the E814 spectrometer. At beam rapidities, the time-of-flight information from the scintillators is useless for separating the proton and deuteron samples. Instead, the momentum of the particles in the fast time-of-flight range can be used for particle identification. Figure 4.23 shows how the deuteron identification is performed in the closed geometry set-up. Figure 4.23a is the particle identification plot shown in Figure 3.8 for charge one particles only. The line running down the middle of this plot is a time-of-flight cut at 0.6 ns with respect to a $v = c$ particle. Only particles to the left of this line are considered in the momentum analysis for deuteron identification. Figure 4.23b shows the projection of the momentum measured by the drift chamber for these fast particles, showing clear peaks at the pion, proton, and deuteron momenta of beam rapidity particles. Particles with momenta between 23.0 GeV/c and 33.0 GeV/c are identified as deuterons. The goal of the deuteron analysis is to count the number of deuterons in the spectrometer to obtain a mean multiplicity plot similar to that obtained for nucleons. It is apparent that there is a contamination in the deuteron sample due to protons. This background is subtracted by multiplying the number of
Figure 4.23: a) Particle identification plot for the closed geometry spectrometer showing the time-of-flight maximum (solid line) used for the beam rapidity deuteron identification. b) Momentum projection for particles below a time-of-flight of 0.6 nsec showing the separation of the proton and deuteron peaks.
RESULTS: DEUTERON SPECTRA

Figure 4.24: a) Beam rapidity deuteron rapidity distributions for Si + Pb collisions (solid line). The dashed line is the Goldhaber fragmentation model prediction using a fermi momentum of 410 MeV/c. b) Beam rapidity deuteron transverse momentum distribution along with the fragmentation model prediction.
Figure 4.25: a) Mean multiplicity per event of deuterons in the spectrometer for Si + Pb, Cu, and Al collisions as a function of $E_t$. b) Comparison of the deuteron, proton, and two proton mean multiplicity per event as a function of centrality for Si + Pb collisions. The curves are drawn to guide the eye.
RESULTS: DEUTERON SPECTRA

deuterons in each momentum interval by the fraction of proton contamination in that momentum interval.

In order to ensure that the beam rapidity deuterons are being identified correctly and the background is being subtracted correctly, a comparison of the rapidity and transverse momentum distributions to the Goldhaber fragmentation model described later can be performed, as it is for the proton distributions. Figure 4.24 shows these distributions for beam rapidity deuterons gating on the mid $E_t$ trigger along with the Goldhaber model fits generated in the same manner as for the protons for Si + Pb collisions. In both figures, the data is represented by the solid lines and the Goldhaber fits are represented by the dotted lines. Good agreement between the model and the data is obtained using a fermi momentum of the projectile nucleons of 450 Mev/c. This value is much higher than the fermi momentum of 270 MeV/c suggested by the proton data. This Goldhaber fragmentation model allows determination of the fermi momentum if the deuteron sample consists entirely of those that have fragmented from the projectile nucleus without any further interaction. But, in heavy ion collisions, deuterons can be present due to other processes, such as coalescence of a proton and neutron. These processes will tend to broaden the transverse momentum and rapidity distributions of the deuterons. If the broader distributions are then analyzed with the fragmentation model, higher fermi momenta will result. The possible extent of the coalescence of deuterons in these collisions will be discussed in Chapter 5.

The beam rapidity deuteron mean multiplicity per event was measured as a function of TCAL transverse energy, as done for the nucleons in Figure 4.22. These results are shown in Figure 4.25a for beam rapidity deuterons from all three targets ( Pb, Cu, and Al ). The trend of the plots is similar to that seen for nucleons from all three targets, only here for the most central Si + Pb collisions, the mean multiplicity of deuterons is at about 0.002. Figure 4.25b shows the comparison of
RESULTS: DEUTERON SPECTRA

protons and deuterons for Si + Pb collisions along with the measured mean multiplicity of two beam rapidity protons per event in the spectrometer. Surprisingly, the deuteron mean multiplicity curve is comparable to that for finding two protons per event. Discussion of this higher than expected mean multiplicity for deuterons will be done in the next chapter.

4.4: PINEUT SEARCH

The deuteron data presented above suggests that there could be a high probability for the coalescence of the proton and neutron to form a deuteron due to the unexpectedly high number of measured beam rapidity deuterons. This result implies that a favorable environment exists to coalesce a particle that has not been shown to exist, but has been speculated to exist, the pineut particle, which is a bound system consisting of a number of neutrons and negative pions.

Theoretical studies of the existence of the pineut have been conducted with mixed results. Experimental searches for pineuts have yielded mostly negative results. Most of these experiments have not attempted to search for pineuts in heavy ion collisions. Most recently, a search for pineuts has been conducted at the Lawrence Berkeley Laboratory Bevelac using 40Ar projectiles at 1.8 GeV/nucleon and 139La projectiles at 1.3 GeV/nucleon on a 238U target, yielding five pineut candidates that were dismissed due to inconsistencies in the events containing the candidates.

A similar search for pineuts in heavy ion collisions has been conducted using the E814 forward spectrometer, but with the major difference that E814 has the ability to search for pineuts at beam rapidity for 14.6 GeV/A Si + A collisions, while the Bevelac experiment searches for pineuts at lower rapidity and lower
incident energies. These recent searches have been undertaken because heavy ion collisions are a favorable environment for pineut production. These collisions are known to produce many pions and the neutrons necessary for pineut formation are already available in the projectile and target nuclei. At the Bevelac, the pineuts are hypothesized to form from the fireball produced in the collision with the fireball and participant nuclei providing the pions and neutrons. In the E814 measurement, the production mechanism differs in that the pineut is formed from neutrons in the projectile that already exist close to each other in phase space since they were originally constrained in the projectile nucleus. The pineut would form if a pion is produced close enough in phase space to allow pineut formation. This section describes the method and results of the search for pineuts using the E814 spectrometer.

The strategy for the E814 pineut search is a simple one. First, all events where a single particle with a charge of -1 and an energy consistent with that of a pineut intersects the two pineut UCAL calorimeter modules will be determined. These events will then be examined for consistency to ensure that the recorded particle originates from the target rather than from an interaction in the apparatus downstream of the target. The rest of this section will describe the strategy in detail and discuss the results of the analysis.

The trigger implemented for the E814 pineut search is a simple energy trigger requiring 20 GeV or more to be deposited in the two pineut calorimeters for those events that have passed the pre-trigger condition. The pineut trigger does not place any requirement on the transverse energy so as not to bias the measurement toward peripheral or central collisions. Data were taken over two running periods in 1989 and 1990 with identical trigger conditions using a 14.6 GeV/A Si projectile incident on targets of $^{208}$Pb, $^{64}$Cu, $^{119}$Sn, and $^{27}$Al. There was no data taking using a Cu target in 1989. The 1990 data taking period uses the same closed geometry
arrangement of the PCAL and the spectrometer as the 1989 run with the exception that the pineut FSCI scintillators are moved by 5 cm in the negative x direction.

The trigger implemented for the pineut search is a simple energy sum trigger requiring that the amount of energy deposited into the two pineut UCAL modules be above a pre-set threshold on the FERA ADC sums. For both the 1989 and 1990 runs, the threshold corresponds to 20 GeV deposited in the UCAL calorimeters, well below the expected two-neutron pineut energy.

<table>
<thead>
<tr>
<th>DATA CUT</th>
<th>Pb</th>
<th>Sn</th>
<th>Cu</th>
<th>Al</th>
<th>Frame</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incident beam on target</td>
<td>301.10^6</td>
<td>338.10^6</td>
<td>135.10^6</td>
<td>311.10^6</td>
<td>484.10^6</td>
</tr>
<tr>
<td>Passed pineut trigger</td>
<td>9278</td>
<td>12104</td>
<td>4092</td>
<td>10024</td>
<td>15079</td>
</tr>
<tr>
<td>Double beam cut</td>
<td>9238</td>
<td>12001</td>
<td>4081</td>
<td>10004</td>
<td>15001</td>
</tr>
<tr>
<td>One minimum ionizing particle in pineut FSCI scintillators</td>
<td>1921</td>
<td>3012</td>
<td>1832</td>
<td>2893</td>
<td>4709</td>
</tr>
<tr>
<td>Require a valid track with</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>proper energy and momentum</td>
<td>21</td>
<td>35</td>
<td>25</td>
<td>34</td>
<td>30</td>
</tr>
<tr>
<td>Magnet shadowing cut</td>
<td>8</td>
<td>11</td>
<td>10</td>
<td>19</td>
<td>11</td>
</tr>
<tr>
<td>Require DC1 hit (1990 only)</td>
<td>6</td>
<td>11</td>
<td>3</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>Event consistencies (see text)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 4.3: List of the offline cuts applied to the pineut data from both the 1989 and 1990 data taking periods. Shown are the number of events for each target surviving the cut. Application of the cuts yield no pineut candidates from the entire sample.
Due to the nature of the relativistic heavy ion collision environment, there are many events where the projectile fragments and the resulting fragments then interact with the material in the detectors, or with the air between the target and calorimeters. These "downstream interactions" are responsible for the background seen in the search for valid pineut events. This is not a problem for the proton analysis due to the large number of true proton tracks found, but in the pineut analysis where relatively few pineut particles, if any, are expected to be found, the downstream interaction background becomes significant. Due to this background, the cuts listed below are designed as consistency checks to ensure that any event passing all of the cuts can only be due to a true pineut particle produced within the target. The events that pass the pineut UCAL energy trigger are analyzed offline. The series of cuts applied to the events is summarized in Table 4.2 along with the number of events surviving each cut for each target. Some of the cuts, described below, differ in the 1989 and 1990 runs since more detectors were implemented for the 1990 run that were more efficient at identifying downstream interactions.

The first cut applied to the triggered events is an examination of the pulse height of the beam scintillators to confirm the Level 1 trigger decision. If that pulse height was greater than that for a charge 14 particle, then more than one beam particle is present in the apparatus during the event and it is eliminated from the analysis. The next cut requires that only one singly charged particle be present in the four pineut scintillators in front of the trigger calorimeters. This cut assumes that if a pineut is produced, there will be no other negatively charged particles from the interaction accompanying it. The largest contribution to this effect would be from accompanying antideuterons, which should appear in the pineut calorimeters with a frequency of much less than the measured antiproton rate of $1.25 \times 10^{-5}$ per event$^{18}$, so this effect is negligible. There is also a requirement that a valid track be present in the spectrometer intersecting the trigger calorimeters as determined by
the drift chambers. The valid track must have a momentum and energy consistent with that expected for a pineut particle. The expected kinematic quantities of each type of pineut searched for here is listed in Table 4.3. Some of the events passing the trigger are due to more than one hit in the calorimeters. These are resolved by the cluster finding algorithm examining the UCAL hits. In some events, there are hits in the drift chambers in areas where no particle originating from the target could reach kinematically and must therefore be a result of downstream interactions. These events are eliminated from the analysis. The series of cuts was identical for both runs to this point and eliminate all but a handful of the events as shown in Table 4.4.

The remaining cuts examine specific detectors to ensure that the data from those detectors is consistent with an event with the accepted particle originating from the target without an interaction in the apparatus downstream from the target. For the 1989 run, an event is eliminated if there is excess neutral particle activity outside of the kinematically accessible range for neutral particles in the spectrometer as determined by energy deposit in the downstream UCAL modules with no corresponding hit in the adjacent FSCI scintillators. For the 1990 run, it is possible to use information from DC1 and the two silicon detectors placed upstream of the target. An event is eliminated if there is no accompanying DC1 hit within five pads of the projected particle track. An event is also eliminated if there is a change in the pulse height measured in the two upstream silicon detectors, indicating that an interaction upstream of the target has occurred. These cuts eliminate all events in both runs.
### Table 4.4: List of the energy and rigidity required for pineuts in the spectrometer along with the calculated acceptance for each type of pineut.

<table>
<thead>
<tr>
<th>Pineut neutron number</th>
<th>Mass</th>
<th>Energy</th>
<th>Rigidity</th>
<th>1989 acceptance</th>
<th>1990 acceptance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^-, 2n$</td>
<td>2.0 GeV/c$^2$</td>
<td>31.49 GeV</td>
<td>31.4 GeV/c</td>
<td>86.6 %</td>
<td>90.4 %</td>
</tr>
<tr>
<td>$\pi^-, 3n$</td>
<td>3.0 GeV/c$^2$</td>
<td>46.15 GeV</td>
<td>46.0 GeV/c</td>
<td>86.2 %</td>
<td>73.0 %</td>
</tr>
<tr>
<td>$\pi^-, 4n$</td>
<td>3.9 GeV/c$^2$</td>
<td>60.80 GeV</td>
<td>60.7 GeV/c</td>
<td>85.9 %</td>
<td>0.0 %</td>
</tr>
</tbody>
</table>

In order to determine the upper limit cross-section for pineut production from the data, it is necessary to determine what percentage of pineuts would be detected by the apparatus, assuming that they exist. A Monte Carlo program was written using the GEANT package for pineut tracking to accomplish this by generating pineut particles. Pineuts are generated by first sampling the negative pion momentum from AGS data of pion production in Si+Pb collisions. The $\pi^-$ momentum is then added to the neutron momentum vector, which is identical to the beam momentum for each neutron varied isotropically over the measured beam momentum spread. The pion transverse momentum is required to be small enough to form a pineut with a binding energy of at least 5.0 MeV. The simulated pineuts are then tracked through the spectrometer using the GEANT package, and the percentage of pineuts intersecting the scintillators and calorimeters are recorded. In addition, if a pineut intersects a calorimeter module, the total energy deposited in the pineut UCAL calorimeters is determined from a parameterization of the energy shower profile. If the energy deposit in the pineut calorimeters is below 20 GeV, then the trigger would not have detected the pineut and that pineut is not recorded in the acceptance calculation. In this manner, the trigger efficiency was determined to be 100 % for the accepted pineuts. The results of this calculation in percent
geometrical efficiency for both the 1989 and 1990 runs are listed in Table 4.4. The acceptances are below 100 % primarily due to interactions of the pineuts with the detector material between the target and the calorimeters.

The results of the pineut search are tabulated in Table 4.5, listing the upper cross section limit for pion production in nanobarns at the 90 % confidence level. The best limit is for Si + Al collisions for two-neutron pineuts at 288 nb.

<table>
<thead>
<tr>
<th>Target</th>
<th>2 neutron pineut</th>
<th>3 neutron pineut</th>
<th>4 neutron pineut</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb</td>
<td>659.7 nb</td>
<td>710.3 nb</td>
<td>1.03 mb</td>
</tr>
<tr>
<td>Sn</td>
<td>466.1 nb</td>
<td>503.0 nb</td>
<td>740.8 nb</td>
</tr>
<tr>
<td>Cu</td>
<td>881.2 nb</td>
<td>1.09 mb</td>
<td>--------</td>
</tr>
<tr>
<td>Al</td>
<td>288.2 nb</td>
<td>312.8 nb</td>
<td>480.3 nb</td>
</tr>
</tbody>
</table>

Table 4.5: Upper limits at the 90 % confidence level for beam rapidity pineut production as measured in the E814 forward spectrometer.
CHAPTER 5: DISCUSSION

The data presented in Chapter 4 contain the information that can now be used to achieve a better understanding of nucleus-nucleus collisions at AGS energies. The particular questions that must be answered concern the extent of the energy deposited by the projectile in the target nucleus. If sufficient energy is deposited, then the possibility of the formation of a hot, thermal system or a quark-gluon plasma exists. The discussion presented in this chapter will focus on the beam rapidity component of the nucleon distributions shown in Chapter 4. These nucleons can be interpreted as projectile fragment nucleons that do not interact inelastically during the collision, in the framework of the Goldhaber fragmentation model. Also, the beam rapidity nucleons are analyzed in terms of a geometrical model in order to extract an in-medium nucleon-nucleon cross-section. The lower rapidity nucleons are those that have interacted with the target nucleus and can be studied in the framework of other models, such as the hydrodynamical Landau fireball model, ARC, and HIJET. Also, comparisons with another AGS experiment, E802, can be made. With this information, the extent of the energy depositions in these collisions can be clarified. This chapter will also examine the beam rapidity deuteron results and explain the high number of deuterons seen in the E814 spectrometer, and will explore the implications of this data for pineut production.
5.1: INTERACTING AND NON-INTERACTING NUCLEONS

As explained in Chapter 4, there appears to be two distinct components to the proton rapidity and transverse momentum spectra. The two components are easily separated in Figures 4.7, 4.9, and 4.15, where there is a clear peaked component centered about the beam rapidity of 3.4 and a second component at lower rapidities. In the initial Si projectile nucleus, all bound nucleons are travelling at beam rapidity, with the addition of fermi momentum. In order for a nucleon to be detected after the collision near beam rapidity, it must not participate in an inelastic interaction. This would shift its rapidity downward below the beam rapidity peak in Figure 4.7. The beam rapidity peak (defined as protons with $y > 3.2$ and neutrons with $y > 3.0$) must be due to proton or neutron fragments of the projectile nucleus that do not interact in the collision. This hypothesis will be explored in more detail in the next section. Beam rapidity nucleons can survive the collision in one of two ways: they could be nucleons that impinge on the periphery of the target nucleus, or have an impact parameter larger than the target radius, and be sheared off of the projectile nucleus. Alternatively, the surviving nucleons could be those that are incident upon the volume of the target nucleus with a small impact parameter. These nucleons will simply travel the diameter of the target without interacting with the target nucleons. By selecting the beam rapidity nucleon component alone, it is not possible to distinguish which of these processes produces the resultant proton from the E814 measurement, but by selecting very central collisions, the probability of the peripheral process is much reduced compared to the central process. The analysis of this type will be explored in more detail in the section describing the geometrical model.
5.2: GOLDHABER FRAGMENTATION MODEL

In the previous section, it is suggested that the beam rapidity nucleons are projectile fragments that do not interact in the collision. In order to test this hypothesis, the data are studied in the framework of the Goldhaber fragmentation model. This model predicts the rapidity and transverse momentum distributions of non-interacting projectile fragments. This section will describe the process used to compare the Goldhaber model to the proton data.

The Goldhaber fragmentation model makes the assumption that nucleons that have not undergone direct inelastic collisions, but are instead emitted from the excited projectile spectator matter are emitted isotropically in the projectile rest frame with a momentum distribution characterized by the momentum of the nucleons when they were bound in the projectile nucleus. In other words, the distribution of the nucleon fragments depends entirely on the fermi momentum of the nucleons in the Si projectile prior to the collision. A detailed discussion of the application of this model to data at AGS energies can be found elsewhere.

The Goldhaber model states that projectile fragments with mass number \( A = 1 \), or nucleons, will have a momentum distribution in the rest frame of the projectile given by the expression:

\[
\frac{d\sigma}{dp} \propto e^{-\sigma^2/2\sigma^2} = e^{-5p_t^2/2p_f^2}, \text{ with } \sigma^2 = \frac{\langle p^2 \rangle}{3},
\]

where \( \langle p^2 \rangle \) is the expectation value of the square of the total momentum of the nucleon and \( p_f \) is the fermi momentum of the nucleon in the projectile nucleus.

This momentum distribution has been sampled using a Monte Carlo simulation that converts the distribution into the rapidity and transverse momentum of the nucleon in the lab frame by generating random angles, theta and phi,
uniformly in spherical coordinates and projecting the momentum into the transverse and longitudinal directions. The simulation then tracks the protons and neutrons through the experimental apparatus using the GEANT tracking package as described earlier. The resulting theoretical distributions in \( y \) and \( p_t \) detected in the acceptance of the spectrometer are accumulated if the simulated nucleons intersect the FSCI hodoscope. In this way, it is possible to compare the simulation results directly to the data. The fermi momentum is a free parameter in the simulation. The simulation results are shown as the dotted lines in Figures 4.7 and 4.9 for the rapidity distributions, and in Figures 4.11 and 5.1 for the \( p_t \) distributions of the nucleon fragments. These predictions are all obtained using a fermi momentum of 270 MeV/c.

The distribution of nucleon momenta in the nucleus has been determined from measurements of high momentum transfer inelastic electron scattering.\(^50\) For nuclei near Si, the measured distribution is approximately Gaussian with a standard deviation of 235 MeV/c. Huang and Feshbach\(^51\) use \( <p^2_t>^{1/2} = 230 \text{ MeV/c} \) to describe fragmentation of oxygen projectiles at 1 GeV/nucleon. More recent data from the Bevelac has been analyzed using the Goldhaber fragmentation model with fermi momenta of 190 MeV/c.\(^52\) The fit using a fermi momentum of 270 MeV/c is consistent with the previously measured value showing that the nucleon beam rapidity data behaves like non-interacting fragments from the projectile nucleus. The slightly higher fermi momentum value seen in the nucleon data could be due to some projectile heating at the higher AGS energies.
Figure 5.1: Comparison of the transverse momentum spectrum of beam rapidity ($y > 3.2$) protons from Si+Pb collisions selecting the middle multiplicity trigger from the open geometry run to the Goldhaber fragmentation model with a fermi momentum of 270 MeV/c (H symbols) and to the HIJET simulation with rescattering (diamonds).
5.3: GEOMETRICAL MODELS

This section will concentrate on the data taken for the mean multiplicity per event of beam rapidity nucleons shown in Figure 4.22 as a function of centrality. A geometrical model\textsuperscript{53} will be described that reproduces the data very well, providing a simple interpretation of the $\langle M \rangle$ data in terms of the interaction probability of the nucleon traversing the target nucleus.

For the most central collisions, corresponding to the right-most points for each target in Figure 4.22, a reasonable assumption is that the high $E_t$ values are due to collisions with complete geometric overlap of the projectile and target nuclear volumes. At these small impact parameters, the path length travelled by the nucleons through the target is very close to the target diameter. With the path length known along with the measured number of non-interacting nucleons per event, the mean free path of the nucleon through the target nuclear matter can be calculated along with its interaction probability, written in terms of an in-medium interaction cross section. This is the first direct measurement of this quantity.

Some corrections must be made to better determine the mean multiplicity per event for each target in the most central collisions. Examining the rapidity spectra of protons in Figure 4.7, there is some background from the lower rapidity protons under the lower half of the beam rapidity peak. The background is eliminated by assuming that the beam rapidity peak is symmetric about beam rapidity ($y = 3.44$) and taking twice the integral of the upper half of the beam rapidity peak in order to determine the background-subtracted mean multiplicity, referred to as $M_b$. $M_b$ is multiplied by the geometrical acceptance correction factor for the beam rapidity protons to obtain the corrected multiplicity, $M_c$. The raw mean multiplicity from Figure 4.22 is referred to as $M_r$. Table 5.1 tabulates the
values of $M_r$, $M_h$, and $M_c$ for all three targets at the most central and peripheral collisions measured.

<table>
<thead>
<tr>
<th>Target</th>
<th>$E$ (GeV)</th>
<th>$M_r$</th>
<th>$M_h$</th>
<th>$M_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>3.5</td>
<td>1.25 (5)</td>
<td>1.16 (5)</td>
<td>1.40 (6)</td>
</tr>
<tr>
<td></td>
<td>8.5</td>
<td>1.02 (24)</td>
<td>0.88 (21)</td>
<td>1.11 (26)</td>
</tr>
<tr>
<td>Cu</td>
<td>4.5</td>
<td>0.73 (4)</td>
<td>0.63 (3)</td>
<td>0.79 (4)</td>
</tr>
<tr>
<td></td>
<td>9.5</td>
<td>0.65 (9)</td>
<td>0.53 (7)</td>
<td>0.66 (9)</td>
</tr>
<tr>
<td>Pb</td>
<td>5.5</td>
<td>0.95 (4)</td>
<td>0.83 (3)</td>
<td>1.04 (4)</td>
</tr>
<tr>
<td></td>
<td>15.5</td>
<td>0.064 (7)</td>
<td>0.039 (4)</td>
<td>0.049 (5)</td>
</tr>
</tbody>
</table>

Table 5.1: Multiplicities of forward protons for Si + Al, Cu, and Pb collisions. $M_r$ is the multiplicity for $y > 3.0$ protons. $M_h$ is the multiplicity for $y > 3.44$ protons times two. $M_c$ is $M_h$ after acceptance correction. Values for the lowest and highest $E$, measured are given for each target. The statistical errors are in parentheses reflecting the error in the last digit(s).

After determining the mean multiplicity per event of beam rapidity protons, it is possible to calculate the mean number of interactions, $<n>$, that the proton makes with nucleons in the target using the equation $<n> = -e^{P_0}$, where $P_0$ is the probability that the nucleon does not interact in the collision. $P_0$ can be determined from $M_c$ using the equation $P_0 = \frac{M_c}{14}$ since there are 14 protons in the Si nucleus.

The values of $<n>$ determined in this manner from the data are 5.66, 3.06, and 2.53
for the Pb, Cu, and Al targets, respectively. From the mean number of interactions, the in-medium interaction cross section, $\sigma_{\text{in}}$, can be calculated using

$$\sigma_{\text{in}} = \frac{\langle n \rangle}{d \cdot \rho}$$

where $d$ is the diameter of the target and $\rho$ is the density of the target medium, which is assumed constant throughout the target volume at 0.16 nucleons / fm$^3$. The in-medium interaction cross sections are calculated to be $28.8 \pm 0.5$ mb for the Pb target, $28.8 \pm 1.8$ mb for the Cu target, and $30.8 \pm 2.5$ mb for the Al target. These numbers are very close to the free p-p interaction cross section value of 29 mb at AGS energies. The calculated interaction cross sections are lower limits on the cross section values since the data can fluctuate in impact parameter by about two fermi.

The calculation described above assumes that the impact parameter of the nucleon on the target nucleus is zero. An improved geometric calculation has been developed to further understand the beam rapidity $<M>$ data. The simulation described below has been extended to interpret the E814 measurements of antiproton production in relativistic heavy ion collisions.\textsuperscript{17}

The geometric simulation is equipped to handle any specified target and projectile nuclear collision and starts by building a target nucleus by computing the nucleon density distribution over the volume of the target using a Wood-Saxon distribution, $\rho(r) = \rho_0(1 + e^{(r-R)/a})^{-1}$, where $\rho_0$ is 0.165 nucleons / fm$^3$ is the density of normal nuclear matter, $r$ is the present distance from the center of the nucleus, and $R$ is the radius of the nucleus, given by $R = 1.143 \cdot A^{1/3}$, and $a$ is the surface thickness. The projectile is built one nucleon at a time, since the distance of each nucleon from the center of the target must be known in order to track them through
the target nucleus. In the projectile, the nucleons are randomly placed by sampling the Woods-Saxon distribution within the volume of the projectile nucleus.

The transverse energy and charged particle multiplicity produced in the collision is calculated from the number of initial nucleon-nucleon collisions that occur during the event. Each nucleon-nucleon collision generates an $E_t$ and $N_c$ that are parametrized from the TCAL and MULT data using gaussian functions. The number of collisions occurring during an event is determined using the mean free path of the nucleons calculated from their free interaction cross sections of 29 mb. If an interaction occurs, $E_t$ and $N_c$ are incremented by the parameterized amount and modified for the expected amount of rescattering to occur from the point of the interaction to the surface of the target nucleus. The parameterization of the centrality measures obtained in this manner are shown in Figure 5.2, compared to the E814 data from the TCAL and MULT detectors. The best agreement to the TCAL data is obtained for the Pb target, while the agreement to the MULT data is very good for the Pb and Al targets.

Each nucleon is tracked in small steps through the amount of target material that it must pass, which is determined in three dimensions. During each step, a random number from 0 to 1 is generated uniformly and compared to the probability that the nucleon interacts during that step length as determined from the free inelastic p-p cross section of 29 mb. If the nucleon does not interact throughout the target volume, it is counted and included in the mean multiplicity per event plot, otherwise the nucleon is not tracked further. The results of this Monte Carlo geometrical simulation for the three different targets measured by E814 are shown in Figure 5.3 along with the proton data. Again there is excellent agreement for the Pb target at high transverse energies. The Al target is overpredicted due to the fact that this model does not include heavier projectile fragments in the simulation, which would reduce $<M>$ for the more peripheral collisions.
Figure 5.2: a) Comparison of the TCAL transverse energy measured for Si + Pb, Cu, and Al targets to the generated $E_t$ from the geometrical model. b) The same comparison of the MULT charged particle multiplicity. The simulation fits are the lines and the data are the points.
Figure 5.3: Comparison of the mean multiplicity per event of beam rapidity protons to the predictions of the geometrical model using a p-p inelastic cross section of 29.0 mb for Si projectiles incident on targets of Pb, Cu, and Al. The model predictions are the lines and the data are the points.
5.4: LANDAU FIREBALL MODEL

The Goldhaber fragmentation model and the geometrical model concentrate on the beam rapidity component of the nucleon data sample. A model designed to interpret the distribution of the lower rapidity component is the Landau fireball model, which is a hydrodynamical model designed to explain relativistic heavy ion collisions in the context of a thermalized fireball of hot, hadronic matter created in the reaction volume. This scenario was first proposed by Landau and has recently been adapted to relativistic heavy ion collisions at AGS energies by J. Stachel and P. Braun-Munzinger. The model is applied below to study the data presented in this dissertation.

The fireball model assumes that the two nuclei involved in the collision, approaching each other with an impact parameter $b$, and are described by spheres of constant density. The number of projectile and target nucleons present in the overlap volume and in the produced fireball, labelled as $N_p$, $N_t$, and $N_f$, respectively, are determined geometrically. A variable parameter of the model is the stopping fraction, defined as $f_s = s \sqrt{1 - \frac{b^2}{R^2}}$, where $R$ is the impact parameter of the combination of the target and projectile and $s$ is an adjustable parameter, as is the temperature of the fireball. The value of $f_s$ is determined by comparing the Monte Carlo calculations described below with the TCAL measured transverse energy shown in Figure 2.3. The physics constants of the fireball are given by:

$$\beta = \frac{p \gamma_p N_p}{\gamma_p N_p + N_t}, \quad y = \tanh^{-1}(\beta), \quad \text{and} \quad E_{cm} = m_n \sqrt{N_p^2 + N_t^2 + 2 \gamma_p N_p N_t}.$$
where the subscripts \( p \), \( t \), and \( f \) refer to the projectile, target, and fireball, respectively.

The Landau fireball model scenario can be expressed in terms of the longitudinal and transverse components of the collision. The model operates on the hypothesis that the nucleons of the colliding nuclei will push, or be squeezed together, creating pressure in the longitudinal direction so that the fireball system expands initially in one dimension in this direction. The initial expansion is described by the entropy of the initial system and manifests itself in the rapidity spectra of the particles that have been emitted, or "frozen out" of the fireball. The longitudinal expansion is followed by thermalization in three dimensions, described by the temperature of the fireball during particle emission. The thermalization process manifests itself in the particle transverse momentum spectra. The behavior of a model assuming that particles are emitted in an isotropically expanding fireball have also been investigated with little success in reproducing the data.55

A Monte Carlo simulation of the fireball model has been developed at SUNY - Stony Brook in order to compare the model to the data shown here.55 The simulation samples the longitudinal and transverse components of the fireball scenario from the equation:

\[
f(y, p_t) = e^{-\frac{(y-y_0)^2}{2\sigma_y^2}} \cdot \sqrt{m_t} \cdot e^{-\frac{p_t^2}{2T^2}}
\]

to obtain the rapidity and \( p_t \) distributions. The variable \( \sigma_y \) is proportional to the logarithm of the ratio of the initial temperature to the freeze-out temperature. The freeze-out temperature is assumed to be identical to the pion mass of 137 MeV and the initial fireball temperature is set to 150 MeV for the simulations shown here. The rapidity distribution of nucleons within the forward spectrometer acceptance is determined from the generated rapidity and \( p_t \) distributions by propagating the emitted particles through the spectrometer using the GEANT package. Full
stopping of the projectile nucleons in the target nucleus is assumed by setting the parameter $f_\pi$ to 1.0.

The simulation is compared to the data in the bottom (most central) plots of Figures 4.7 and 4.8. The fireball model reproduces the data very well in the $y < 3$ regime as it does for the transverse energy measurements shown in Figure 2.3. There is no reproduction of the beam rapidity peak seen in the rapidity distributions, since the fireball model assumes full stopping, or no surviving beam rapidity particles, contrary to what is measured. The fireball model, however, predicts identical distributions for protons and neutrons, unlike the data presented here. Also, the predicted inverse slope parameters (temperatures) are independent of rapidity, which is not what is seen in the data presented in Figures 4.17 and 4.20.

5.5: A RELATIVISTIC CASCADE

The models presented to this point have focussed on only one component of the nucleon spectra - the beam rapidity nucleons or those at lower rapidity. These models are each based on simple physics assumptions. Another approach to understanding the processes involved in relativistic heavy ion collisions is to assume that neither a quark gluon plasma or a thermalized fireball exist, and that the collision can be described entirely by known hadronic physics processes. These processes include the production of particles and the excitation and decay of resonances, and the absence of any collective phenomena. A study of this type has been conducted by Y. Pang, T. J. Schlagel, and S. H. Kahana with their model, A Relativistic Cascade, or ARC for short.56

ARC is a Monte Carlo simulation of the collision of the target and projectile nuclei. ARC builds both the target and projectile nuclei nucleon-by-nucleon,
generating their position and momentum vectors, including their fermi momentum. The simulation tracks all of the initial nucleons during the reaction and consults tables of measured nucleon-nucleon cross sections to determine when a nucleon-nucleon interaction occurs. When an interaction does take place, one of two processes is invoked to determine what, if any, secondary particles are produced. The first process is a direct production model whereby a number of pions are produced via the mechanism $NN \rightarrow NN\pi\pi$. The second process takes into account the nucleon resonances, such as $NN \rightarrow \Delta\Delta\pi$ to determine the produced secondaries. The number of produced pions for each interaction typically ranges from 1 to 7 at AGS energies. ARC tracks all initial and secondary particles during the collision and handles any further interactions that the particles are involved with in a similar manner. The effect of rescattering is included in the simulation. Particles escaping the reaction volume are tracked into the forward 0.8 degree cone of the E814 spectrometer closed geometry and the rapidity spectra of the nucleons are generated along with the $dN/dy$ plots. The ARC results using the resonance formulation for the mean multiplicity per event of beam rapidity protons detected in the E814 spectrometer from Si + Pb collisions are shown in Figure 5.4 showing excellent agreement with the data. This agreement extends to the $dN/dy$ comparison for Si + Pb collisions shown in Figure 5.5 and to the Boltzmann temperature parameters as a function of rapidity shown in Figure 5.6. The resonance production form of ARC also agrees well with the E802 data shown in Figures 5.5 and 5.6.
Figure 5.4: Comparison of the E814 measured mean multiplicity per event of beam rapidity protons for Si + Pb collisions (solid line) and the ARC resonance production form prediction (dashed line). The lines are drawn to guide the eye.
Figure 5.5: Comparison of the E814 dN/dy distribution for protons from Si + Pb collisions with the ARC resonance production form prediction (dashed line). The squares are the corresponding E802 distribution from Si + Au collisions.
Proton Inverse Slope Parameters

Figure 5.6: Comparison of the E814 and E802 proton Boltzmann temperature parameters as a function of rapidity. The dotted line is a Gaussian extrapolation of the E802 data. The solid line is the ARC resonance form prediction and the dashed line is the ARC direct production form prediction.
Another simulation code designed for studying heavy ion collisions at AGS energies is the HIJET simulation. HIJET is similar to ARC in that it attempts to reproduce every aspect of the data without assuming any thermal or collective behaviour during the collision. HIJET considers the nuclear collision as a superposition of independent nucleon-nucleon collisions using the free interaction and production cross sections in each N-N collision. The projectile and target nucleons are distributed randomly in the nuclear volume using a Woods-Saxon potential as done in the ARC simulation and the geometric model. HIJET continues by assigning a fermi momentum to each nucleon by sampling a Gaussian distribution with a momentum width $\sigma = 200$ MeV/c with the constraint that the total momentum of the nucleons in the nucleus rest frame is zero. The two nuclei are allowed to collide in the nucleon-nucleon center-of-mass system with a user-specified impact parameter. The spectator nucleons are not allowed to interact and their momenta are not modified throughout the collision. The participant nucleons are tracked through the target in small steps where the probability of an interaction with a target nucleon is determined from the mean free path of the projectile nucleons in the target, which is taken to be 2.3 fm. HIJET differs from ARC in that only when an interaction of two nucleons that have not previously been involved in an interaction occurs is the energy loss of the nucleons calculated and any secondary particles produced. When a secondary particle is determined to be produced by comparing to the known free cross sections at or near AGS energies, it is formed only after an adjustable formation time. Interactions of secondary particles with nucleons and with each other are considered in this simulation only as long as they are within the target or projectile nucleus, accounting for the process of rescattering
DISCUSSION: HIJET

whereby the secondary particles are multiply scattered as they travel through the target. Each interaction of the secondaries in the target will result in a higher probability that they will leave the reaction volume in the backward direction, or opposite to the direction of travel of the projectile. It has been shown, using the TCAL transverse energy data, that the rescattering process is important by comparing the data to the HIJET results with and without the rescattering process included in the simulation.\textsuperscript{15,19}

HIJET has been used as an event generator for the nucleons that are then tracked through the E814 apparatus using the GEANT package to produce rapidity, transverse energy, and transverse momentum spectra of protons detected in the forward spectrometer. Comparisons of the transverse energy generated by HIJET in the TCAL detector are shown in Figure 2.3 along with the data for Si + Pb, Cu, and Al collisions. Comparison of the HIJET predictions of the neutron rapidity spectra can be seen in Figure 4.9. Here, HIJET does reproduce the beam rapidity peak seen in the data, but poorly reproduces the distribution contributing to the lower rapidity, or interacting, protons. Also, the number of nucleons detected in the spectrometer as generated by HIJET are lower than what is measured, showing that HIJET overpredicts the extent of stopping in these collisions. The HIJET prediction for the transverse momentum distribution of beam rapidity particles detected in the spectrometer acceptance using a fermi momentum of 200 MeV/c is shown in Figure 5.1, generating a curve with a narrower width than the data, as expected. The bump in this prediction at the larger values of $p_t$ are probably due to contamination from interacted protons.
DISCUSSION: COMPARISON WITH E802

5.7: COMPARISON WITH E802

Experiment E802 is an AGS-based experiment that measures relativistic heavy ion data with an acceptance for protons complementary to that of E814. E802 has measured the dN/dy distributions for protons and deuterons, kaons, and pions detected in their spectrometer.\(^4\) Figure 4.6 shows the comparison of the acceptances of the E814 closed geometry, the E814 open geometry, and E802 spectrometers. Comparisons between the E814 closed geometry and E802 are very tenuous due to the large gap in the \(p_t\) acceptance of the two experiments. This problem is remedied by the increased acceptance in the open geometry running of E814, where there is a small overlap in the acceptances of the two experiments to better facilitate comparisons. A comparison can be seen for protons in the respective measurements of rapidity distributions and the Boltzmann inverse slope parameters of the two experiments\(^5\)\(^8\), shown in Figures 5.5 and 5.6. These figures demonstrate the excellent agreement between these two independent measurements in both the dN/dy distribution and the inverse slope parameters.

5.8: BEAM RAPIDITY DEUTERONS

This section will summarize the data taken for beam rapidity deuterons and will propose explanations for the large number of deuterons detected in the E814 forward spectrometer.

The process of identifying beam rapidity deuterons is illustrated in Figure 4.23, showing clear separation of the proton and deuteron peaks. A further check can be made on the quality of the beam rapidity deuteron identification to determine that the sample is indeed one of non-interacting deuterons from the
collision by applying the Goldhaber fragmentation model to the deuteron rapidity and transverse momentum distributions using the same procedure applied for the proton distributions. The same Monte Carlo simulation is used for the deuteron comparison as for protons, except the mass of the deuteron is used in the GEANT tracking and the generated initial momentum distribution of deuterons differs. For deuterons, the fragment mass number is now 2, so the initial momentum distribution given by the Goldhaber model becomes:

$$\frac{d\sigma}{dp} = e^{-\frac{298p^2}{p_f^2}}.$$

Again, the fermi momentum, $p_f$, is left as a free parameter. The measured rapidity and $p_t$ distributions of beam rapidity deuterons detected in the spectrometer are shown by the solid lines in Figure 4.24. The dashed lines are fits of the fragmentation model showing agreement to the data using a fermi momentum of 450 MeV/c. As mentioned in Chapter 4, this large value suggests that some process other than fragmentation is responsible for the deuteron sample, such as coalescence of a proton and a neutron into a deuteron.

The mean free path model described previously in this chapter can also be applied to the beam rapidity deuteron mean multiplicity per event plot shown in Figure 4.25 to determine if this data can be understood in the same manner as the proton data. Using the mean free path model on the proton data, an in-medium interaction cross section of 29 mb is measured, which corresponds to the free p-p cross section at AGS energies. Continuing this argument, it would be expected that the free p-d cross section at AGS energies of 65 mb should be measured from the deuteron mean multiplicity per event. For the highest $E_t$ measurement at 15 GeV for deuterons from Si + Pb collisions, the mean multiplicity is 0.0012. Assuming that there are 14 deuterons present in the original projectile nucleus, which is an extreme assumption, an upper limit for the deuteron in-medium cross section can be
calculated. The value of \( P_0 \) (the probability that the deuteron did not interact) becomes 0.0000857. This yields a mean number of interactions within the target of \( \langle n \rangle = 9.36 \), which translates into an in-medium interaction cross section for deuterons of only 41.1 mb, much lower than the expected 65 mb free cross section. In other words, far more beam rapidity deuterons are being measured in the spectrometer than expected from applying the interpretation of the proton measurement. In order to reproduce the 65 mb cross section, a value of \( \langle n \rangle = 14.8 \) would be necessary, or a mean multiplicity per event of \( 5.3 \times 10^{-6} \), which is more than two orders of magnitude (227 times) lower than the measured mean multiplicity in the most central events.

What could be the cause of the high abundance of beam rapidity deuterons in the spectrometer? If the deuteron has a smaller effective radius as it traverses the nuclear medium compared to the radius of a free deuteron, then the observed in-medium interaction cross section would be lower than the free value. Another, more likely, explanation is that after the collision, there will be protons and neutrons that have survived the collision without interacting. Assuming that the mean multiplicity per event for finding a proton and a neutron is identical to that of finding two protons, the value from the data shown in Figure 4.25 can be used, which is 0.0036 for the most central collisions. The protons and neutrons are initially very close to each other in phase space since they are confined within the projectile nucleus. Without interacting, the beam rapidity protons and neutrons will still be close to each other in phase space and have a probability to coalesce into a deuteron. The excess deuteron yield measured here could be due to coalescence of beam rapidity deuterons after the collision.
Figure 5.7: Comparison of the E814 beam rapidity deuteron mean multiplicity per event with the geometrical model prediction as a function of TCAL transverse energy for Si + Pb collisions. The geometrical model assumes that 25% of surviving proton-neutron pairs coalesce into deuterons.
Figure 5.8: Comparison of the estimates of the cross sections for beam rapidity neutrons, deuterons, tritons, and two-neutron pionuts for Si + Al collisions. The pionut production cross section estimate is three orders of magnitude above the E814 upper limit.
In order to obtain an estimate for the possible extent of coalescence of protons and neutrons into deuterons at beam rapidity, the geometrical model can again be applied. This is done by allowing a fraction of the pairs of beam rapidity protons and neutrons surviving the collision to coalesce into deuterons. This coalescence fraction is left as a free parameter. A comparison of the geometrical model prediction for the mean multiplicity distribution of coalesced deuterons as a function of TCAL $E_t$ using a coalescence fraction of 0.25 is shown in Figure 5.7, showing good agreement at the higher $E_t$ values. The disagreement for low $E_t$ is probably due to an increased number of deuteron projectile fragments and heavier fragments surviving the collision at the higher impact parameters.

5.9: PINEUT PRODUCTION

As described in Chapter 4, the E814 pineut search found no pineut candidates despite favorable conditions for the coalescence of the constituent particles into a pineut including two, three, or four neutrons in heavy ion collisions. The best upper limit on the cross section for pineut production from this measurement, tabulated in Table 4.5, is 228 nb for Si + Al collisions at the 90% confidence level for producing a two neutron pineut, which implies that if the pineut particle exists, its production cross section is lower than the sensitivity of the experiment.

The expected two neutron pineut cross section for Si + Al collisions can be estimated from the known neutron, pion, and deuteron yields. Since the pineut measurement is not biased towards centrality, the entire TCAL $E_t$ range must be considered. The mean multiplicity per event of beam rapidity protons for Si + Al collisions averages 1.25 over the entire transverse energy range. This leads to a
beam rapidity proton cross section of about 2061 mb. From the average mean multiplicity per event of beam rapidity deuterons of 0.35, the beam rapidity deuteron cross section is about 577 mb. Assuming that the triton cross section scales linearly from the proton and deuteron cross sections, a beam rapidity triton cross section of about 162 mb is estimated. The pion production cross section can be obtained from the Sanford and Wang measurements of 13.5 GeV \( p + \text{Be} \) collisions.\(^{47}\) The \( p + \text{Be} \) values must be multiplied by a factor of 4.0 to obtain the production cross section for 14.6 GeV/A \( \text{Si} + \text{Al} \) collisions, as determined by E802\(^{8}\). In this manner, the pion cross section is estimated to be about 2.23 mb. From the equation

\[
\sigma_{\pi^-} = \sigma_{\text{triton}} \left( \frac{\sigma_{\pi^-}}{\sigma_{\text{proton}}} \right) ,
\]

the two neutron pion cross production cross section is estimated to be 175 \( \mu b \). This is about three orders of magnitude above the upper limit for pion production set in this analysis. The cross section estimates above are summarized graphically in Figure 5.8.

\[5.10: \text{SUMMARY AND CONCLUSIONS}\]

This dissertation is concerned with studying the physics processes involved in relativistic heavy ion collisions at AGS energies by measuring the properties of nucleons initially in the projectile nucleus after the collision. The study has concentrated on measurements of beam rapidity, or noninteracting, nucleons surviving the collision. These data were presented in Chapter 4. Chapter 5 has been concerned with interpreting the data based on several models in the hope that the models can successfully predict the nucleon distributions. This section will summarize the work in the context of the state of the matter existing in the extreme
conditions of the relativistic heavy ion collision environment: Is a quark-gluon plasma state being created or can the data be explained in terms of known hadronic processes?

From the transverse energy measurements made by the TCAL shown in Figure 2.3 and the mean multiplicity per event of beam rapidity nucleons in the spectrometer shown in Figure 4.22, it is apparent that the transparency of the collisions is very small since few particles survive in the longitudinal direction and a large amount of energy deposit is seen in the transverse direction for central collisions. Measurements of the rapidity distributions, dN/dy, for protons over the rapidity acceptance of the spectrometer again demonstrate the low degree of transparency at AGS energies since there is no beam rapidity peak in the dN/dy spectrum (Figure 4.18). A lack of transparency implies that most of the nucleons are undergoing interactions that deposit energy into the collision system, which is necessary for quark-gluon plasma formation.

A simple estimate of the energy density achieved in 14.6 GeV/A collisions of identical nuclei can be performed. This is done by assuming that the projectile and target nuclei stop each other completely. In this case, the density of the nuclear medium was evaluated by Goldhaber to be \( \rho = 2 \gamma_{cm} \rho_0 \), where \( \rho_0 \) is the density of normal nuclear matter (0.16 nucleons/fm\(^3\)). The total volume of the system is Lorentz contracted and given by \( V = \frac{A}{\rho_0 \gamma_{cm}} \), where \( A \) is the mass number of each nucleus. The energy deposited in the volume is the number of nucleons, \( 2A \), times the energy carried by each nucleon, which is \( \gamma_{cm} mc^2 \), or \( E = 2A \cdot \gamma_{cm} mc^2 \). The energy density, \( \varepsilon \), is the energy divided by the volume, or \( \varepsilon = 2\gamma_{cm}^2 \varepsilon_0 \), where \( \varepsilon_0 = mc^2 \rho_0 = 0.15 \text{ GeV/fm}^3 \) is the energy density of normal nuclear matter. For \(^{28}\text{Si} + ^{208}\text{Pb} \) collisions, \( \gamma_{cm} = 1.8 \) giving \( \rho = 4 \rho_0 \) and \( \varepsilon = 1 \text{ GeV/fm}^3 \), which is over six times the energy density of normal nuclear matter. These values are very close.
to those required for QGP formation (see Figure 1.1). The low degree of transparency shown here implies that conditions are approaching those that are necessary to produce a QGP.

The hypothesis that the processes involved in heavy ion collisions at AGS are mostly hadronic is backed up by the success of the ARC and HIJET simulations in reproducing the nucleon data. Both of these models assume that there is no QGP creation, thermalized behavior, or collective processes (other than rescattering) dominating the collision. The ARC code, in particular, suggests that there are many interactions occurring during the collision, with much particle creation and resonance decay. These multiple collisions, even though only about three collisions are needed for some thermalization, produce a degree of thermalization as seen in Figure 5.6. There is also multiple scattering in the system producing the rescattering effect. But, ARC assumes that no phase transition in the collision is necessary to reproduce the results – only known hadronic processes.

A quark-gluon plasma can also be formed by heating up the system to about 200 MeV without compression. The Boltzmann temperature from the proton m_t spectra are shown in Figures 4.17 and 4.20 to approach 180 MeV at y = 2.7, again suggesting that conditions are close to what is necessary for QGP formation. The success of the Landau fireball model, which assumes particle emission from a thermalized fireball in the system, in predicting the low rapidity component of the nucleon spectra is also suggestive of a high enough temperature present in the system to form a thermalized volume. But, the ARC simulation, relying on purely hadronic processes, is also successful in reproducing the low rapidity nucleon spectra.

From examination of the data presented in this dissertation, it is clear that in heavy ion collisions at the AGS energies of 14.6 GeV/A, a very hot and dense system has been created, closely approaching the conditions predicted for the
formation of a quark-gluon plasma. If a QGP is being formed in these collisions, it is not created very often, or it has too short a lifetime for detection using the methods applied in this dissertation.

The AGS has recently completed construction of a booster that will allow acceleration of Au ions. First data using Au projectiles have been taken in April 1992. Studies using the Au projectiles will include high sensitivity studies such as experiment E864, which plans to conduct an exhaustive search for strangelets and other exotic particles. Also, CERN is modifying the SPS for acceleration of Pb ions beginning in 1994. If the QGP is not found in these larger systems, then it will in all probability be seen at the higher energies, which will be accomplished by the Relativistic Heavy Ion Collider (RHIC) currently being constructed at BNL and scheduled for completion in 1997. RHIC will use the AGS as an injector of Au ions and will collide them at 200 GeV per nucleon. These collision energies should be sufficient to easily create the temperatures and densities necessary to produce a quark-gluon plasma. The implementation of the new machines should help us achieve a better understanding of the relativistic heavy ion environment and enable us to successfully detect and study the quark-gluon plasma.
17. S.V. Greene, et. al., to be published in Nucl. Phys. A.
53. B.S. Kumar, S.V. Greene, and J.T. Mitchell, Yale no. 40609, unpublished.