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Time-of-flight particle identification results from central Si-Si and Si-W collisions at 14.6 × A GeV/c

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Rice University, 1992
RICE UNIVERSITY

TIME-OF-FLIGHT PARTICLE IDENTIFICATION RESULTS FROM CENTRAL Si-Si AND Si-W COLLISIONS AT 14.6×A GeV/c

by

CHENGNAN CHIOU

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE

DOCTOR OF PHILOSOPHY

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Abstract

Time-of-Flight Particle Identification Results from Central Si-Si and Si-W Collisions at $14.6 \times A \text{ GeV/c}$

by

Chengnan Chiou

Momentum spectra of $\pi^-$, $K^-$, $p$ and $d$ have been measured from central collisions of $14.6 \times A \text{ GeV/c}$ Si beam on Si and W targets at rapidity $1.9 < y < 2.1$. The inverse slope parameters $T_0$ obtained by an exponential fit with the transverse mass spectra in transverse kinetic energy are found to be $T_0(\pi^-) < T_0(K^-) < T_0(p) < T_0(d)$. This result is predicted by a radially expanding flow model. From integrated results, the $K^-/\pi^-$ ratios, $(2.7 \pm 0.3)$ % from Si and $(2.4 \pm 0.2)$ % from W, are consistent with $pp$ collision results. The deuteron production rates can be explained by a relativistic coalescence model.
Acknowledgements

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Chapter I

Introduction

The main objective of relativistic heavy-ion experiments is to study nuclear matter under extreme conditions of high temperature and/or high baryon density and to look for indications of a phase transition from hadronic to quark matter: the Quark-Gluon Plasma (QGP), a new state of matter [1-7]. As an introduction to this topic, we have a short review of quantum chromodynamics (QCD). QCD is the theory of the strong interaction at the quark level and predicts the phase transition that we are dealing with. Next, we explain what a quark-gluon plasma is and how to produce it in the laboratory and how to detect it. Finally, we review some results from current heavy-ion programs at the Brookhaven AGS and the CERN SPS and time-of-flight differences of particles.

There are many technical terms and acronyms in relativistic heavy-ion physics. I will do my best to explain every new term when it is first used. If not, the new term will be explained in a later relevant section or in Appendix A. The collaboration of our experiment is listed in Appendix F.
1.1 Quantum Chromodynamics

Quantum field theory is the language we use to describe the process of the creation, interaction, and annihilation of elementary particles. A summary of the basic forces and elementary particles is given in Appendix B. The fundamental idea of quantum field theory is that all particles are quanta of the corresponding physical fields. Forces are described by quantum field theories incorporating a gauge symmetry principle [8,9,10].

For example, photons are the quanta of the field which describes the interaction between charged particles. Gluons are the quanta corresponding to the strong force field. \( W^\pm \) and \( Z^0 \) bosons are the quanta corresponding to the weak force field. It is these quanta, or gauge bosons, that are exchanged in the interactions between the quarks and leptons.

Gauge symmetry is the invariance of the Lagrangian under a group of continuous transformations (Lie group) whose parameters are functions of space-time coordinates. There are two kinds of gauge symmetries, unbroken and spontaneously broken. A gauge symmetry requires the existence of massless gauge vector fields. Spontaneous breaking of a gauge symmetry gives masses to some of the fields.

The Abelian group \( U(1)_{em} \) describes the interaction of photons with charged particles and the non-Abelian group \( SU(3)_c \) describes the color interactions of gluons with quarks and with themselves. The color interaction between gluons is the result of the "non-Abelian" nature of the group and is the origin of the asymptotic freedom property. The \( U(1)_{em} \) and the \( SU(3)_c \) groups are examples of unbroken gauge symmetries. The group \( SU(2)_W \times U(1)_Y \) of electroweak interactions is an example of spontaneously broken gauge symmetry, which gives masses to \( W^\pm \) and \( Z^0 \) bosons.
QCD is the theory of the strong interaction at the quark level and was developed in the early 1970s after the discovery of asymptotic freedom in non-Abelian gauge theories. Eight massless gluons form a representation of the SU(3) group and couple to colors. The quarks also carry colors; each type or flavor of quark has three colors, a triplet representation of the underlying SU(3) color group.

1.1.1 The SU(3) Color Symmetry

The color quantum number was first proposed by Greenberg [11] in 1964 to solve a difficulty in hadron spectroscopy. One example of this difficulty is $\Delta^{++}(uuu)$, made up of three $u$ quarks. $\Delta^{++}$ is the lowest mass baryon made of three $u$ quarks, i.e., it is in state of zero relative orbital angular momentum (S state), hence its spin is just the vector sum of the quark spins. The intrinsic spin of $\Delta^{++}$ is $\frac{3}{2}$, which means that the spins of the three $u$ quarks are aligned parallel. Therefore the spatial and spin states of the $\Delta^{++}$ are symmetric under interchange of any two $u$ quarks, but we know that quarks are fermions and the total wavefunction of $\Delta^{++}$ should be antisymmetric. If we introduce a new hidden quantum state, color, which is antisymmetric under quark interchanges, the overall antisymmetry of the $\Delta^{++}$ total wavefunction is restored. Three different quark-quark interchange are possible within a baryon so that color must be a three-fold symmetry; SU(3) was the simple choice.

Hadrons are color singlets. Then how do we observe the color effects [9]? All the electroweak field particles (photon, $W^\pm$, and $Z^0$) are colorless and can only couple to a quark-antiquark pair of the same color. Hence certain electroweak processes are affected by
the color. We take

$$e^+ + e^- \rightarrow \text{hadrons}$$

as an example to demonstrate the color effect. According to the quark model the reaction can be separated into two processes. First the $e^+$ and $e^-$ annihilate into a virtual photon and the photon converts into a quark-antiquark pair. Then the quark and antiquark fragment into hadrons. The fragmentation has unit probability because only final hadrons are observed, never free quarks. Therefore the rate in

$$e^+ + e^- \rightarrow \text{hadrons}$$

is the same as in

$$e^+ + e^- \rightarrow q + \bar{q}.$$ Comparing it with

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

we get

$$\frac{\sigma(e^+ + e^- \rightarrow \text{hadrons})}{\sigma(e^+ + e^- \rightarrow \mu^+ + \mu^-)} = N_c \sum_f Q_f^2,$$

where $N_c$ is the number of colors and the sum is carried over the active quark flavor.

Experimental results support the three-color hypothesis.

### 1.1.2 Asymptotic Freedom

A key property of QCD, which makes it very different from QED, is asymptotic freedom, i.e., quarks becomes asymptotically free at small distances. This property, which is generally inherent in non-Abelian gauge theories, was discovered in 1973 by D. Gross, F. Wilczek, and H. D. Politzer [12,13].
We can use the running coupling constant in QCD, $\alpha_s$, to show this property \[14\]. The $\alpha_s$ takes the form
\[
\alpha_s(Q^2) = \frac{g^2(Q^2)}{4\pi} = \frac{12\pi}{(33 - 2N_f)\log(Q^2/\Lambda^2)},
\]
where $N_f$ is the number of quark flavor and $\Lambda$ is the QCD scale parameter to be determined by experiment. $\Lambda$ is about $0.2\ GeV$. We see that as long as the number of quark flavors is less then 17, $\alpha_s$ tends to zero for large $Q^2$, or equivalently, at small distances.

1.1.3 Quark Confinement

The reverse side of asymptotic freedom is the increase of $\alpha_s$ as the distance between quarks increases. At a distance $r \approx 1/\Lambda \approx 10^{-13}\ cm$, $\alpha_s$ apparently diverges. This divergence heralds the breakdown of perturbation theory.

The hypothesis of strict confinement was suggested to explain the negative results of the experimental search for free quarks. We hope that confinement is a corollary of non-Abelian gauge theories. However, we do not yet have a proof of confinement, nor a clear understanding of this phenomenon in the framework of QCD.
1.2 Quark-Gluon Plasma

1.2.1 Phase Transition of Nuclear Matter

At high density and/or high temperature, the property of asymptotic freedom in QCD predicts that a phase transition occurs in nuclear matter. In this phase transition, hadronic matter, i.e., matter composed of baryons and mesons, is converted into a quark-gluon plasma consisting of quarks and gluons that are no longer confined within a hadronic bag, but are free to move in a larger volume. The phase transition is expected to require a baryon density of more than \(8\rho_0\) (\(\rho_0 = 0.17/fm^3\) the saturation density of nuclear matter), or a temperature \(T\) about 200 MeV.

The conjectured phase diagram of QCD matter is shown in Fig. 1.1 [2]; the abscissa is net baryon density (\(\rho_{nm}\)) and the ordinate is temperature (\(T\)). Normal nuclear matter appears at 1 \(\rho_{nm}\) at near zero \(T\). The region of the phase transitions corresponding to quark deconfinement and chiral symmetry restoration is indicated by grey area. Above \(T_c\), hadrons dissolve into quarks and gluons. Above the temperature of chiral symmetry restoration quarks are massless. The two critical temperatures may be coincident. The indicated trajectories show two regions for probing the QGP with heavy-ion collisions: in the high baryon density fragmentation region among the hot, compressed fragments of the colliding nuclei or in the high temperature central region among thermally produced particles. The region in the QGP phase at low \(T\) and high \(\rho\) is the condition which may exist at the center of neutron stars, while the region near \(\rho = 0\) and high \(T\) is thought to be the condition of the early universe at \(t \approx 1 \times 10^{-6}\) seconds.
FIG. 1.1: Phase diagram of QCD matter
1.2.2 Crude Estimate of $T_c$ and $\rho_c$

Critical Density $\rho_c$

The radius of a nucleus is proportional to $\approx 1.2 A^{1/3}$ fm. The core radius of the proton is about 0.6 fm. In other words only about 1/8 of the nuclear volume is filled by the quark cores of its nucleons. However, the separation between the quark bags shrinks when nuclear matter is compressed until all "empty space" between them is squeezed out at a nuclear density $\rho_c \approx 8 \rho_0$. Beyond that density, the nucleons may be expected to dissolve into one continuous region occupied by quarks, i.e., quark matter.

Critical Temperature $T_c$

Let us estimate what temperature we need to fill space completely with pions [15]. Neglecting the pion rest mass and setting the Boltzmann constant $k_B = 1$, the number density of pions is

$$n_\pi = 3 \int \frac{d^3p}{(2\pi)^3 e^{p/T} - 1} = \frac{3}{\pi^2} \zeta(3) T^3$$  \hspace{1cm} (1.2)

Space is filled with pions if

$$n_\pi V_\pi = \frac{3}{\pi^2} \zeta(3) T_c^3 \cdot \frac{4\pi}{3} R_\pi^3 = \frac{4}{\pi} \zeta(3) (T_c R_\pi)^3 = 1$$

Taking a pion radius $R_\pi \approx 0.6 fm$, this gives

$$T_c \approx 0.85 R_\pi^{-1} \approx 280 \text{ MeV},$$  \hspace{1cm} (1.3)

where we have used $\hbar c \approx 200$ MeVfm to convert inverse length into energy. This value of $T_c$ is overestimated, because other mesons are excited as well, leading to a much higher hadron density near $T_c$, which is thus reduced to about 200 MeV.
1.2.3 Plasma Production by Heavy-Ion Collisions

Collisions between heavy nuclei at relativistic energies are tremendously complicated processes evolving from a simple initial state, two nuclei in their ground states, to highly complex final states involving hundreds, even thousands of free particles at RHIC energy. Why do we study it? Because the only way we know today of obtaining hadronic states with high density and/or high temperature is by ultra-relativistic heavy-ion collisions.

Two scenarios of how a high energy density could develop in nuclear collisions have been presented. The schematic illustration of the two scenarios is shown in Fig. 1.2 [16].

First, the "low-energy" or stopping scenario one assumes that a large target nucleus is able to stop an approaching high-energy projectile. In this case a "fireball" is formed out of the colliding parts of the nuclei, containing a large fraction of baryons. As described by Landau [17], this fireball expands hydrodynamically as an ideal gas until the freeze-out density for pions is reached. This expanding fireball model is confirmed by the AGS E814 experiment [18] at 10 GeV/n Si beam energy as shown in Fig. 1.3. The curves in the figure are calculated for an expanding fireball assuming full stopping in the collision.

Second, in the "ultra-high energy" or scaling scenario one assumes that nuclei are essentially transparent and that high energy density is formed out of hadronizing strings between the nuclei after they have passed through each other. At SPS energy (200 GeV/n), the WA80 experimental data [19] cannot be described without assuming some transparency as shown in Fig. 1.4. The dashed curve is calculated for an expanding fireball assuming full stopping for the Au target. The solid curves incorporate 28%, 22%, and 12% transparencies for Cu, Ag, and Au targets.
FIG. 1.2: Nuclear transparency in high energy collisions
FIG. 1.3: Transverse energy distributions from E814
FIG. 1.4: Transverse energy distributions from WA80
1.2.4 Rapidity Range and Center-of-Mass Energy

The kinematic relationship between the rapidity \( y \) range and CM energy at high energies

\[
\Delta y \approx \ln \frac{s}{m_pm_t}
\]

(1.4)
is derived in Appendix A where \( m_p \) is the projectile mass and \( m_t \) the target mass. A kinematic landscape is given in Fig. 1.5. The outer “vee” is the phase space limit of the rapidity of the incident nucleons. The inner, solid vee delineates fragmentation regions of width \( \Delta y = 2 \), as observed in \( pp \) collisions. The dashed lines indicate the wider fragmentation regions of width \( \Delta y = 4 \). The horizontal lines indicate beam energies from some current accelerators and from RHIC.

1.2.5 Space-Time Evolutions of Heavy Ion Collisions

The various regimes encountered in a central relativistic heavy-ion collision are conveniently summarized in the space-time diagram of the collision, Fig. 1.6 [3,20,21]. This diagram shows the evolution of the matter along the collision axis (z) as a function of time in the center-of-mass (CM) frame. Prior to colliding, the projectile and target nuclei travel essentially along the light cone until they meet at the origin. After the collision, the remains of the nuclei, the nuclear fragmentation regions, emerge from the collision again along the forward light cone. The matter between the fragmentation regions is in the central rapidity region as shown in Fig.1.2.

The central region is left highly excited by the collision. The first instant after the collision, \( \leq 1 \text{ fm/c} \) in the local rest frame, is the time of formation of excitations, i.e., quarks, anti-quarks, and gluons. Once excitations have been created, the matter enters the
FIG. 1.5: The kinematic landscape for heavy-ion collisions
kinetic regime, where we can treat the system in terms of interacting excitations. During this phase, interactions tend to bring the system into local thermodynamic equilibrium. After this phase, we may employ relativistic hydrodynamics to describe the evolution of the system. If the matter comes into local thermal equilibrium as a QGP, it will undergo the hadronization and chiral symmetry breaking transitions during the hydrodynamic phase. Then, depending on how strongly coupled the emerging hadronic matter is, the system will either further evolve in the hydrodynamic phase and then freeze out or emerge directly from the hadronization transition. Thus we can roughly divide the evolution of the collision into three phases:

The compression phase —

It generates hot compressed hadronic matter with high energy density and it contributes to nonequilibrium background. The fireball of hot hadronic matter transforms into a QGP beyond the critical temperature and/or density.

The plasma phase —

The thermodynamic equilibrium of the quarks, anti-quarks, and gluons is reached.

The expansion phase —

The hot plasma cools off to hadronic matter as the temperature falls with the expansion of the fireball. With the cooling of the plasma, a mixed phase first appears containing the hadronic matter as well as QGP. After further cooling, the mixed phase hadronizes into a hadron gas system. The system now expands adiabatically as a free distribution of pions and finally freezes out.
FIG. 1.6: A space-time diagram of ultra-relativistic nuclear collisions
1.2.6 Plasma Signatures

Some possible signatures for experimental probes of the formation of a QGP in relativistic heavy-ion collisions are listed in Table 1.1 [22].

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<td>Dilepton spectrum</td>
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**TABLE 1.1: Experimental probes for QGP**

**HBT interferometry**

HBT or Bose-Einstein interference allows a measurement of the dimensions of the interaction region from which the bosons are emitted. This method is analogous to the method used in radio-astronomy to measure the angular dimensions of radio sources, the Hanbury-Brown and Twiss (HBT) effect [23].

**Direct photons**
Pions are formed at the surface in the late stages of the collisions and carry very little information about its history. If a photon is produced in a QGP, it leaves the hot plasma with a very small probability of interacting in the outer freeze-out region, about 200 to 300 times smaller than that of a hadron, and therefore carries information about the initial stages of the interaction. Direct photons are produced via the processes $gq \rightarrow \gamma q$ and $q\bar{q} \rightarrow \gamma g$. The $\gamma/\pi$ ratio gives an indication about collective effects by measuring volume-to-surface emission.

**Multiplicities and energies of secondaries**

Knowing multiplicity and energy of the hadronic secondaries allows us to reconstruct the initial energy density, if we know the longitudinal formation length. The initial transverse size is given by the nuclear radii. The formation length can be estimated from nuclear stopping experiments.

$\langle p_T \rangle$ vs $dN/dy$

The form of the $dN/dy$ dependence of $p_T$ indicates the nature of the phase transition [24-27]. In hadronic matter, Hagedorn [28] has predicted that $\langle p_T \rangle$ must increase to an asymptotic value at high energy density. If the QGP is created, the temperature of the system can rise in accordance with the Stefan-Boltzmann law ($\epsilon \propto T^4$). Since $T$ is related to $\langle p_T \rangle$ and $\epsilon$ is proportional to $dN/dy$, the second rise in $\langle p_T \rangle$ as a function of $dN/dy$ will be a possible signature of the QGP.

The imminent presence of a phase transition with large latent heat shows up as a plateau in the rise of temperature with increasing energy density. Put in simple words, the idea is that when the critical temperature $T_c$ is reached, additional energy is required to convert the hadronic phase into the QGP phase. The temperature remains constant and
only continues to rise when the phase change has been completed.

The $p_T$ distributions

The transverse momentum distribution of hadronic secondaries is expected to increase with multiplicity, since the multiplicity is related to the initial energy density and a higher energy density should result in stronger collective flow.

Particle ratio

The measurement of particle ratios may give information on the flavor distribution at the early stages of the process and the nature of the plasma expansion process.

Strangeness enhancement

Strange particle production is expected to be a useful probe for the dynamics of hadronic matter under extreme conditions whether or not a QGP is formed. If a QGP is produced, there are several reasons to suppose that it would give an enhancement in strange particle production. Gluons are produced abundantly in a QGP, and gluon-gluon collisions give rise to quark-antiquark pairs. Strange $q\bar{q}$ pairs have the same coupling to gluons as non-strange pairs. At high temperature, the higher mass of the $s$ quark does not significantly inhibit $s\bar{s}$ pair production relative to light quark pairs as this is no longer large compared to the available energy. Moreover, $s\bar{s}$ production is expected to be favored, since in a baryon-rich environment, the abundance of $u$ and $d$ quarks will suppress further production of $u\bar{u}$ and $d\bar{d}$ pairs through Pauli blocking. It is thus to be expected that strange particle abundance will be enhanced in a QGP relative to that observed in normal hadronic collisions.

As was shown by Rafelski and Müller [29], strange quarks can be produced much more easily in the quark-gluon plasma. The reasons for this effect include a much lower energy threshold and a much larger efficiency of strangeness production by gluons as opposed to
light quarks. The large phase-space density of gluons in the deconfined phase, commanding 16 independent degrees of freedom, facilitates the reaction rate for the process $gg \rightarrow s\bar{s}$, being an order of magnitude larger than characteristic rates for strangeness production, e.g., $NN \rightarrow NK\Lambda, \pi\pi \rightarrow KK$ in the hadronic gas phase. Considerably enhanced production of strange hadrons in AA, as compared to pp, collisions would therefore signal the intermediate existence of a quark-gluon phase; strange antibaryons and multi-strange baryons ($\Xi, \Omega$) are probably the most sensitive signals, because they are difficult to produce in secondary reactions involving nucleons or pions.

**J/ψ suppression**

If a pure QGP is created, then, due to Debye screening the $J/ψ$ can no longer be bound. Accordingly, its production rate could be significantly suppressed. As pointed out by Matsui and Satz [30], color charges are screened in the deconfined quark-gluon phase. The linearly rising, confining potential that binds a $c\bar{c}$-pair into charmonium states $J/ψ, ψ'$, etc., is replaced by a short-range, screened potential in the new phase, which does not support a bound state if $T > 1.2 T_c$. Therefore the formation of charmonium should be suppressed, if a quark-gluon plasma is formed. Since it takes about 1-2 fm/c until the $J/ψ$ state is formed out of a newly created $c\bar{c}$-pair, this suppression should be alleviated for fast moving states which can escape from the fire ball before the $c\bar{c}$-pair can dissociate. Thus the suppression should be most notable at small momenta.

**Dilepton spectra**

If the system is in thermal equilibrium, the dilepton spectrum should fall exponentially with the pair mass, in contrast to power law fall-off for Drell-Yan production. Thermalization will also destroy the memory of the collision axis. Therefore thermal pairs should have an
isotropic angular distribution. Drell-Yan pairs are predicted to be aligned with the incident beam axis. Due to the difference between the

\[ q\bar{q} \rightarrow e^+e^-(\mu^+\mu^-) \]

and

\[ \pi\pi \rightarrow e^+e^-(\mu^+\mu^-) \]

production mechanisms, the production of low-mass lepton pairs will be enhanced.
1.3 Some Results from Current Heavy-Ion Experiments

Current some heavy-ion experiments at the Brookhaven AGS and the CERN SPS are listed in Table 1.2 [5,6,7].

<table>
<thead>
<tr>
<th>BNL</th>
<th>14.6 GeV/n $^{16}O$ and $^{32}$Si beams</th>
<th>Detectors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measurements</td>
<td></td>
</tr>
<tr>
<td>E802</td>
<td>Particle Spectra, Correlation</td>
<td>Mag Spectr, TOF</td>
</tr>
<tr>
<td>E859</td>
<td>HBT KK Correlation</td>
<td></td>
</tr>
<tr>
<td>E810</td>
<td>$V^0(K^0, \Lambda, \bar{\Lambda})$</td>
<td>TPC, TOF</td>
</tr>
<tr>
<td>E814</td>
<td>Forward Spectra, $E_T$</td>
<td>Calorimeters</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CERN</th>
<th>60 and 200 GeV/n $^{15}O$ and $^{32}$Si beams</th>
<th>Detectors</th>
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<tr>
<td></td>
<td>Measurements</td>
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<td>NA34</td>
<td>Particle Spectra</td>
<td>Mag Spectr, TOF</td>
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<tr>
<td>NA44</td>
<td>HBT KK Correlation</td>
<td></td>
</tr>
<tr>
<td>NA45</td>
<td>$e^+e^-$ Pairs</td>
<td></td>
</tr>
<tr>
<td>NA35</td>
<td>$V^0(K^0, \Lambda, \bar{\Lambda})$</td>
<td>Streamer Chamber, Cal</td>
</tr>
<tr>
<td>NA36</td>
<td>$V^0(K^0, \Lambda, \bar{\Lambda})$</td>
<td>TPC</td>
</tr>
<tr>
<td>NA38</td>
<td>$\mu^+\mu^-$ Pairs, $\phi$</td>
<td>Dimuon Spectr, $4\pi$ Cal</td>
</tr>
<tr>
<td>WA80</td>
<td>Multiplicity,$E_T$, Photon</td>
<td>Mult Detectors, Cal</td>
</tr>
<tr>
<td>WA85</td>
<td>$V^0(\Lambda, \bar{\Lambda}), \Xi, \bar{\Xi}$</td>
<td>$\Omega$ Spectr, MWPC</td>
</tr>
</tbody>
</table>

TABLE 1.2: Current some heavy-ion experiments

Cal: Calorimeter; Mag Spectr: Magnetic Spectrometer; Mult: Multiplicity; MWPC: Multwire Proportional Chamber; TOF: Time-of-Flight System; TPC: Time Projection Chamber

They are all fixed-target experiments. Beams up to mass number $A \approx 30$ have been available since Fall 1986 at both places. The usual predicted signals for QGP, as shown in the last section, rely on the high temperature and baryon-free central rapidity region. The rapidity interval in current heavy-ion experiments is 3.4 at the AGS and 5.3 at the
CERN SPS. We really have no clear and separated central region as shown in Fig. 1.5. For discussions on the experimental setup of each experiment, see the proceedings of the Quark Matter meeting [5,6,7].

To define the centrality of the interaction we measure either the electromagnetic or the hadronic energy with an electromagnetic or a hadronic calorimeter, respectively. That is why most experiments have calorimeters. In a TPC detector, which can track a large amount of produced particles, we can use the multiplicity of each event to determine the centrality, because the multiplicity of produced particles is proportional to the energy released in the collision. In more central collisions, more energy is released. This can be shown in in Fig. 1.7 from E814 [31].

The main goal of E814 and WA80 was to measure the global observables, e.g., transverse energy, forward energy, and charged particle pseudorapidity densities with calorimeters. We already have used their results from transverse energy distributions in section 1.2.3 discussing the nuclear stopping. Some results from other experiments are given below.
FIG. 1.7: Multiplicity versus transverse energy from E814

Fig. 1.7 shows the measured multiplicity versus the transverse energy measured in the target calorimeter from Pb target. The two variables have a linear relationship.
FIG. 1.8: Particle yields from E802

E802 and NA34 measured particle spectra and correlations. Fig. 1.8 is a plot of $dN/dy$ for $\pi^\pm$, $K^\pm$, and protons for pBe, pAu, and central Si+Au collisions [32]. The rapidity distribution of $K^+$ differs significantly in shape and peak position from that of $\pi^\pm$ for central Si+Au collisions, even though they have similar shapes for pBe and pAu. The $K/\pi$ ratio gradually increases from pBe to central Si+Au collisions.
Fig. 1.9 shows ratios of $K^+/\pi^+$, $K^-/\pi^-$ production versus transverse momentum $p_T$ in central S+W collisions at rapidity $1.0 < y < 1.3$. Results from $pp$ collisions are shown by the curves for comparison [33].
FIG. 1.10: $V^0$ results from NA35

The three figures in Fig. 1.10 show the ratio of mean $V^0$ multiplicity to total negative multiplicity for pp, pS, and S+S interactions. The point at $\langle h^- \rangle \sim 100$ corresponds to a central trigger [34]. The results show a clear increase in the ratio between pS and central S+S for all three $V^0$ species, by a factor from 1.5 to 3.
FIG. 1.11: Mass spectrum of $\mu^+\mu^-$ pairs in O+U interactions from NA38

In Fig. 1.11, the dimuon production in 200GeV/n O+U interactions, studied by the NA38 collaboration, shows that $\Psi$/Continuum, the parameter S, decreases with increasing $E_T$ and $(S$ at high $E_T)/(S$ at low $E_T) = 0.64 \pm 0.06$ [35]. The rate of production of the $J/\Psi$ was evaluated by the ratio $S$ of the number of $J/\Psi$'s to the number of the continuum mass spectrum which are in the $J/\Psi$ mass region ($2.7 - 3.5$ GeV/$c^2$).
FIG. 1.12: A fully reconstructed event with a $\Xi^-$ candidate from WA85

This figure shows a fully reconstructed event with a cascade candidate. The uncorrected $\Xi^-$ to $\Xi^-$ ratio is $0.43 \pm 0.07$ for S+W data and $0.27 \pm 0.06$ for p+W data [36].
FIG. 1.13: The rapidity distribution for negative tracks from E810

This figure shows the rapidity distribution for negative particles for the Au target [37] along with the results of E-802 [38]. The pion mass was used to calculate rapidity for the data. The agreement is good, considering the totally different techniques used, and the small overlap in phase space coverage.
FIG. 1.14: The rapidity distribution for positive minus negative from E810

This figure shows the "proton" rapidity distributions for Au and Cu targets [37]. We assume that $\pi^+$ production is identical to $\pi^-$ and neglecting the $K^+$ contamination. The proton mass was used to calculate rapidity for the results of positive minus negative. The different nuclear stopping power for Au and Cu targets can easily be seen from the results.
The $1/N_{ev}(dN/dp_T^2)$ vs $m_T$ plot for $\Lambda$'s and $K^0_s$ from both Au and Cu targets [39]. The $m_T$ ranges correspond to a transverse momentum range of $0 < p_T < 1.0$ GeV/c. All of the data is represented by exponentials. The effective temperatures for the fireball is found to be $\sim 150$ MeV for $\Lambda$'s and $K^0_s$'s on both Au and Cu targets.
The $\Lambda$ and $K_s^0$ production for Si+Cu and Si+Au collisions are shown as a function of negative particle multiplicity [39]. There is no enhancement on strangeness from the results.
1.4 Particle Identifications

The difference in time-of-flight, $\Delta t$, between the pairs $(\pi K)$, $(Kp)$, $(\pi p)$, and $(pd)$ as a function of momentum is shown in Fig. 1.17.

The formula

$$\Delta t = 3.34 \times (\sqrt{1 + \frac{m_i^2}{p^2}} - \sqrt{1 + \frac{m_j^2}{p^2}}) \text{ ns}$$  \hspace{1cm} (1.5)$$

has been used, where $m_i$ and $m_j$ are the rest masses and $p$ is the momentum. The flight path is 1 meter. With a 14m flight path, to separate $\pi^-$ from $\bar{p}$ up to 5-6 Gev/c and $\pi^-$ from $K^-$ up to 2.5-3 Gev/c, we require that the Root-Mean-Square (RMS) time resolution of the time-of-flight hodoscope be better than 150 picoseconds.
FIG. 1.17: The time-of-flight difference, $\Delta t$, in 1 meter flight path.
Chapter II
Experimental Setup

Our experiment, AGS E-810 [40], was performed using a 14.6 × A GeV/c silicon beam from the Alternating Gradient Synchrotron (AGS) at the Brookhaven National Laboratory (BNL) to bombard different targets, e.g., silicon (Si) and tungsten (W). The major pieces of equipment in E-810 included the BNL Multi-Particle Spectrometer (MPS), three time projection chamber (TPC) modules, and the MPS time-of-flight (TOF) hodoscope. In this chapter, we first introduce the accelerator complex at BNL, then give a detailed description of the three major pieces of equipment in our experiment, and lastly, discuss the triggers and interaction rates.

2.1 The AGS-Tandem Complex

The accelerator complex at Brookhaven is shown in Fig. 2.1 [41]. The AGS was commissioned in 1960 to accelerate protons to 33 GeV. The protons from the linear accelerator complex (linac) are injected into the main ring of the AGS and are kept on a circular orbit 807 m in circumference by 240 magnets. The acceleration of the protons in AGS is produced by ten radio-frequency transmitters, each of which provides about a 20 KeV energy boost when the proton beam passes through. The strength of the magnetic field in the ring is synchronized to the acceleration of the protons, hence the name “Synchrotron”. The magnet configuration which provides beam focusing gives rise to the name “Alternating Gradient” or “Strong Focusing”.
FIG. 2.1: The accelerator complex at BNL
The focusing of the beam particles to the vicinity of their equilibrium orbit by magnetic forces in a synchrotron is characterized by the field gradient index, $n$, where

$$n = -(r/B)(\partial B/\partial r).$$  \hspace{1cm} (2.1)

Increasing $n$ strengthens the vertical focusing forces at the expense of the radial, while decreasing $n$ has the opposite effect. Radial stability requires $n < 1$, which imposes limits on the strength of both focusing forces [42].

In the AGS, the magnets are built of successive segments having, alternately, $n$ large and positive and $n$ large in magnitude but negative. The first segment focuses vertically but defocuses radially. The opposite happens in the second segment. However, the net result for both vertical and radial motion is focusing. The gradient index in AGS is 0.628 ($36^\circ$).

From 1984 to 1986, a beam line was constructed at BNL linking the AGS and Tandem Van de Graaff facilities to transfer ions ($A \leq 32$) produced at the Tandem to the AGS. In 1992, a booster synchrotron will be completed. The booster ring is 1/4 the AGS diameter and will provide three services: higher proton currents, higher polarized proton beam intensity, and acceleration of beams of mass up to gold from the Tandem to energies at which they can be fully stripped for further acceleration in the AGS.

The current fixed target program at the AGS is the first round of the ultimate Relativistic Heavy Ion Collider (RHIC) project [16,22,44]. RHIC is now under construction and is scheduled to run in 1997. RHIC will consist of two rings of superconducting magnets in a 3800 m circumference tunnel. Each ring will accelerate a beam of heavy ions, up to the mass of gold, at energies up to 100 GeV/nucleon. The beams will be initiated at the Tandem, injected into the Booster, and then sent to the AGS. From the AGS, the ions will
be extracted in bunches and transferred to one of the two collider rings. In 1997, we will have two 100× A GeV/c gold beams colliding with each other to produce the conditions of the early universe shortly after the “Big Bang”, a state of high temperature and low baryon density. Some performance estimates of RHIC are listed in Table 2.1 [45].

<table>
<thead>
<tr>
<th></th>
<th>Au</th>
<th>p</th>
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<tbody>
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<td></td>
</tr>
<tr>
<td>Bunch spacing(nsec)</td>
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<td></td>
</tr>
<tr>
<td>Collision angle</td>
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<tr>
<td>Free space at crossing point(m)</td>
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<table>
<thead>
<tr>
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<th>Au</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. particles/bunch</td>
<td>$1 \times 10^9$</td>
<td>$1 \times 10^{11}$</td>
</tr>
<tr>
<td>Top energy(GeV/u)</td>
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<td>250</td>
</tr>
<tr>
<td>Emittance(π mm.mrad)</td>
<td>60</td>
<td>20</td>
</tr>
<tr>
<td>Diamond length(cm rms)</td>
<td>22</td>
<td>20</td>
</tr>
<tr>
<td>Luminosity(cm$^{-2}$sec$^{-1}$)</td>
<td>$\sim 2 \times 10^{26}$</td>
<td>$1.4 \times 10^{31}$</td>
</tr>
<tr>
<td>Lifetime(hr)</td>
<td>$\sim 10$</td>
<td>&gt; 10</td>
</tr>
<tr>
<td>Beam-beam tune spread/crossing</td>
<td>$3 \times 10^{-4}$</td>
<td>$4 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

**TABLE 2.1: Some RHIC performance estimates**
2.2 The AGS E-810 Experiment

The AGS experimental area in FY 1990 is shown in Fig. 2.2 [46]. Our experiment, E-810 — “A search for Quark Matter (QGP) and Other New Phenomena Utilizing Heavy Ion Collisions at the AGS”, was performed in the MPS area using the A1 beam line. The three TPC modules, the tracking detectors, were located inside the MPS magnet and the TOF hodoscope was positioned 14 m downstream from the target.

2.2.1 Experimental Layout

The experimental layout is shown in Fig. 2.3 and the list of detector sizes and positions is shown in Table 2.2. The heavy ion beam was incident along the z direction and went through these detectors. $S_1$, $S_5$, $S_7$, and $S_8$ were scintillation counters where $S_1$ and $S_5$ were hole counters. They were used as beam halo counters to veto interactions upstream of

<table>
<thead>
<tr>
<th>Detector</th>
<th>Size</th>
<th>Position (cm)</th>
</tr>
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<tbody>
<tr>
<td>$S_1$</td>
<td>$10'' \times 10'' \times 3/8''$</td>
<td>-1066</td>
</tr>
<tr>
<td></td>
<td>hole $3.5'' \times 8''$</td>
<td></td>
</tr>
<tr>
<td>$S_2$</td>
<td>$6.5'' \times 6.5'' \times 3/8''$</td>
<td>-1063</td>
</tr>
<tr>
<td>$C_3$</td>
<td>$6'' \times 6'' \times 1/4''$</td>
<td>-1033</td>
</tr>
<tr>
<td>$PWC5$</td>
<td>$12'' \times 6'' \times 6''$</td>
<td>-998</td>
</tr>
<tr>
<td>$TOF_I$</td>
<td>$7'' \times 7'' \times 1/4''$</td>
<td>-960</td>
</tr>
<tr>
<td>$S_5$</td>
<td>$12'' \times 12'' \times 3/8''$</td>
<td>-390</td>
</tr>
<tr>
<td></td>
<td>hole 4'' diameter</td>
<td></td>
</tr>
<tr>
<td>$PWC6$</td>
<td>$12'' \times 6'' \times 6''$</td>
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</tr>
<tr>
<td>$S_6$</td>
<td>$3'' \times 3'' \times 1/16''$</td>
<td>-300</td>
</tr>
<tr>
<td>$S_7$, $S_8$</td>
<td>$5'' \times 5'' \times 1/4''$</td>
<td>-295</td>
</tr>
<tr>
<td>$S_{10}$, $S_{11}$</td>
<td>$5'' \times 5'' \times 1/4''$</td>
<td>100</td>
</tr>
<tr>
<td>$S_9$</td>
<td>8'' diameter</td>
<td>960</td>
</tr>
</tbody>
</table>

TABLE 2.2: List of detector sizes and positions
FIG. 2.2: AGS experimental area
FIG. 2.3: E-810 experimental layout
the target. $C_3$ was a plastic Čerenkov counter and its signals were stored for later software cuts, i.e., to select events of signal $> 75\%$ of the mean silicon signal. $F_{3w}$ denotes the right-hand signal and $F_{3w}$ the left-hand signal of the TOF front, or start, counter for the TOF time reference. PWC5 and PWC6 were two multiplane proportional wire chambers (PWC) used to measure x and y positions and angle of a particle entering the MPS. $S_{10}$ and $S_{11}$, located above and below the beam just in front of the TPC, were used to select central collision events which had a substantial signal in each of the scintillation counters. $S_9$, located 8 meters downstream of the target and centered on the beam, was a $Z^2$ veto counter to veto on high $Z$ fragments in the beam region. The pulse height from $S_9$ of each event was recorded for later software cuts. For "central" events, a threshold of $Z \sim 1.5$ was chosen.

2.2.2 The Multi-Particle Spectrometer

The Multi-Particle Spectrometer (MPS) is a C magnet 457 cm long by 183 cm wide, with a 122 cm gap between the horizontal pole faces ($15' \times 6' \times 4'$). The magnet rests on hydraulic pads which allow a $30^\circ$ rotation about a pivot near the forward end. The magnet was run at 5.0 kGauss between the pole faces in the upward vertical direction, bending positive particles to the right. A field map was used to reconstruct events and extrapolate particle tracks to the time-of-flight hodoscope.

The z axis is defined to be the central longitudinal axis of the magnet, positioned midway between the pole faces and centered between the sides. The $z = 0$ point is defined at the pivot, 6 feet from the center of the MPS. The incident beams were along the z axis. The y axis is defined along the magnetic field direction and the x axis is to the left from
the beam direction as shown in Fig. 2.3.

2.2.3 **The Time Projection Chamber Modules**

The TPC system [47] was chosen as the tracking detector in this experiment because it measures true three-dimensional points along the tracks, a very significant advantage for track reconstruction. In order to have good event reconstruction in high-multiplicity ( > 100) events, it is important to optimize the two-track resolution by having a large number of independent readout elements. Therefore we have used rows of short (about 1 cm) anode wires parallel to the beam direction and a low-diffusion gas (79 % argon, 16 % isobutane and 5 % dimethoxymethane) known to be stable at high gain in order to achieve this fine segmentation. The x and z coordinates of a track are determined by the active wire position and the y coordinate is derived from the drift time of the signal. Use of the short anode wires precludes using dE/dx for particle identification.

The TPC system consists of three separate modules, each approximately 60 cm high \( \times \) 65 cm wide \( \times \) 47 cm long. The readout is achieved by 36 rows (12 per module spaced 3.8 cm apart) of 256 short anode wires (2.54 mm spacing), with the wire number giving the \((x, z)\) coordinates and the drift time the \(y\) coordinate. For a three module TPC system there are \(3 \times 12 \times 256 = 9216\) readout channels, each of which collects data in 1024 time bins. The hybrid electronic circuits which perform the readout, including the time-to-digital convertors (TDCs), are mounted directly on the chamber, reducing interconnections.

The TPC was positioned inside the MPS magnet in a region of excellent field uniformity as shown in Fig. 2.3. The MPS magnet was run at 5.0 kG. The beam passes through the approximate center of the TPC volume. The measured beam tracks were used to calibrate
the TPC measurements both with the magnet off (alignment runs) and with the magnet on \((E \times B\) calibrations). There were corrections for deviations of the position measurements due to horizontal components of the electric field near the edges of the field cage. A few hundred tracks gives sufficient data to align the TPC to an accuracy of 100 microns and to measure the drift velocity to better than 1\%. The TPC modules were operated at about 330 V/cm with a drift velocity of \(2.3 \times 10^6\) cm/s.

The rms position resolution, as measured by fitting Si beam tracks, was 0.6 mm in x, 0.25 mm in y, and about 5 mm in z. Using secondary tracks from Si interactions, the rms deviations from fits were 0.9 mm in x and 0.75 mm in y. The momentum resolution was strongly correlated with the number of coordinates on a track. In order to use only reasonably accurate data for momentum dependent variables, tracks whose measured momentum is larger than an average resolution of \(\Delta p/p\) of 25\% were removed. For example, for full length tracks (31 or more hits) the resolution \(\Delta p/p^2 = 0.01\) \((GeV/c)^{-1}\) so tracks of 24 \(GeV/c\) or higher are removed. Tracks with fewer than eight hits are discarded [48].

### 2.2.4 The Time-of-Flight System

In experiments in nuclear and particle physics, the use of large-area scintillator hodoscopes giving the time-of-flight and the impact position of the particle is very common [49,50,51,52]. The usual technique adopted to achieve the best performance is that of coupling a fast photomultiplier tube (PMT) to the two ends of each paddle of the hodoscope. The information on the position is given by the time difference, \(\Delta t\), measured by the two PMT’s. The arithmetic mean between the two time differences, \(\Delta t_1\) and \(\Delta t_2\), measured by the two PMT’s relative to another counter (we called it the TOF front counter) placed upstream, gives the
<table>
<thead>
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<tbody>
<tr>
<td>Risetime</td>
<td>1.5 ns</td>
</tr>
<tr>
<td>Transit time variation</td>
<td>0.25 ns</td>
</tr>
<tr>
<td>Gain at 2200 V</td>
<td>$3 \times 10^7$</td>
</tr>
<tr>
<td>Quantum efficiency at peak</td>
<td>26 %</td>
</tr>
</tbody>
</table>

**TABLE 2.3**: Characteristics of the XP2020 photomultiplier

time-of-flight, independently of the impact position.

The TOF hodoscope in the MPS consists of 30 paddles, (actually 32, but the last two paddles are bad). Each paddle consists of a piece of 2" thick × 6" wide × 72" high Pilot F scintillator, two fish-tail shape UVT plastic light guides and a pair of Phillips XP2020 PMT’s. The specifications of Pilot F scintillator are listed in Table 2.4 and the characteristics of Phillips XP2020 PMT’s are listed in Table 2.3 [53].

**TOF Electronics**

The block diagram of the electronics used to process the TOF signals is shown in Fig. 2.4 [54,55]. We took anode and dynode signals of each PMT. The anode signals were stored in an ADC (analog-to-digital convertor) for slew correction and dynode signals were used for timing. The TOF front counter, $F_3$, was viewed by two Hamamatsu R2083 PMT’s (rise

<table>
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</tr>
<tr>
<td>Attenuation length</td>
<td>300 cm</td>
</tr>
<tr>
<td>Decay constant of main component</td>
<td>2.1 ns</td>
</tr>
<tr>
<td>Wavelength of maximum emission</td>
<td>425 nm</td>
</tr>
</tbody>
</table>

**TABLE 2.4**: Specifications of Pilot F scintillator
time 0.7 ns) and was located 10 m upstream of the target. The $F_{3e}$ and $F_{3u}$ signals were used for the time reference of the TOF hodoscope.

The anode output from each PMT was delayed about 800 ns via a 75Ω cable, then was digitized by an analog-to-digital converter (ADC, LRS-2249, 1024 channels, 0.25 pC per channel). The dynode output from each PMT was sent via a 75Ω cable and then inverted and matched to a 50Ω cable before input to a discriminator (LRS 621). The threshold of the discriminator was set to 50 mV. The output from the discriminator was delayed about 677 ns via a 75Ω cable, then was input to another discriminator (Phillips 710). The delay cables and the discriminators were placed in a temperature controlled cold room to reduce variations of the cable transit time due to temperature fluctuation. The threshold was set to 100 mV and the output was sent to stop a time-to-digital converter (TDC, LRS 2228, 2048 channels, 50 ps per channel) placed in the control room. The purpose of these delays was to wait for the trigger from the fast electronics trailer. The anode output from the TOF front counter was split into two equal signals and one signal was sent to an ADC and the other to a TDC.
TOF LOGIC

PMT

Anode

800ns

Delay

2249

621L

677ns

Delay

710

2228

Dyode

In cold room

Tof Paddle top/bottom

In control room

PMT

155ns

Split

2228

Tof front counter
F3e/F3w

Trigger
from
Fast
Trailer

710

Delay

710

Delay

429

ADC gates

2228

2249

429

LeCroy 8 channel TDC
2249 LeCroy 12 channel ADC
429 LeCroy quad logic fan in/fan out
621L LeCroy quad discriminator
710 Phillips octal discriminator

FIG. 2.4: TOF electronics
2.3 Interaction Rates and Triggers

Since the beam passed directly through the center of the TPC's, the beam rate was held to $< 5000$ ions/sec in order to limit the amount of ionization deposited in the TPC's. Typical beam rates during the run were $\approx 2500$ per spill incident on the target. Target thicknesses were chosen to be a few percent of a radiation length to minimize gamma ray conversions which would give incorrect multiplicities. The targets used in the data analysis were 1.2 mm Si and 0.1 mm W.

The beam and trigger were defined as the following, see Fig. 2.3,

\[ beam = \bar{S}_1 \cdot S_2 \cdot (C_{3e} \land C_{3w}) \cdot \bar{S}_5 \cdot S_6 \cdot \bar{S}_7 \cdot \bar{S}_8 \quad (2.2) \]

\[ trigger = beam \cdot \bar{S}_9 \cdot S_{10} \cdot S_{11} \quad (2.3) \]

As explained in the experimental layout, $S_1, S_5, S_7,$ and $S_8$ were used as beam halo counters to veto interactions upstream of the target. $C_{3e}$ and $C_{3w}$ were signals from the Čerenkov counter to identify the incident silicon ions. $S_2$ and $S_6$ were used as yes counters. Therefore the beam was defined as Eq. 2.2.

The trigger was based on a scintillation counter, $S_9$, 8 m downstream of the target which vetoed on high Z fragments in the beam region to select central collision events and a pair of counters, $S_{10}$ and $S_{11}$, just behind the target to select interactions from the target. This pair of counters was 20 cm behind the target and 2.5 cm above and below the beam line. $S_{10}$ and $S_{11}$ were used to select high multiplicity events, which had a substantial signal in each of the counters. Therefore the trigger was defined as Eq. 2.3. The trigger rate is about 1/85 for the Si target, i.e., one trigger out of 85 beam particles. For the W target, the trigger rate is about 1/120.
A detailed block diagrams of the trigger logic in the fast trailer as well as other system logic drawn by Ed. Platner are given in Appendix C.
Chapter III

Data Acquisition and Analysis

3.1 Data Acquisition

The data-acquisition system for E-810 [56] is all done through standard FASTBUS [57]. All CAMAC devices are read out by a FASTBUS module (Strück 320 branch driver). The host computer is a VAX-750 and it is interfaced to the FASTBUS by a computer interface module (CFI). Data reading and formatting is done by the SLAC scanner processors (SSP’s) resident in the FASTBUS system. The SSP program is written in VAX-11 MACRO assembly language by R. Hackenburg. A multiprocess software system on VAX computers is used to communicate with the SSP’s, to record the data, and to monitor the experiments.

The block diagram of the DAQ system is shown in Fig. 3.1. The VAX-750 host computer is connected to the CFI in FASTBUS crate 0 by a specially adapted UNIBUS module. The data recording medium is a 6250 bpi magnetic tape capable of speeds of 125 inches per second. The present FASTBUS configuration consists of three FASTBUS crates. Each crate contains a SSP. The SSP’s are used as intelligent masters in FASTBUS. They are programmable modules with their own CPU’s and data memories [58]. The cable segment port on the SSP’s allows the SSP to be used as a buffered segment interconnect (BSI). This feature gives us the ability to assemble a multicrate FASTBUS data-acquisition system and provides us with essentially direct access to all the crates, even though there is only one CFI in one FASTBUS crate (crate 0). This crate also contains the FASTBUS branch driver
FIG. 3.1: The MPS data-acquisition system — a hardware block diagram
(FBD) for accessing the CAMAC branch through the FASTBUS memory module.

Since we operate with a fixed target accelerator, the memory module allows us to buffer data during beam spills and read it into the VAX host between spills for recording on magnetic tape. Detector systems, e.g., time projection chambers, the TOF hodoscope, and various ADC's, are connected to the CAMAC and FASTBUS front-end modules.

During the accelerator beam spill the SSP's go through their device readout cycle in the following way:

(1) When an event of interest is detected by the fast electronics trigger logic, a trigger pulse is sent to the main SSP (SSP0).

(2) SSP0 disables any further triggers and reads a module in a CAMAC crate to obtain a trigger classification.

(3) SSP0 passes trigger classification information to the other SSP's and issues commands to start up the other SSP's on the cable segment.

(4) Each SSP reads out the modules specified in its own device list as downloaded in the beginning of the run. Each trigger class has its own, separated device readout list, and each SSP has its own set of these lists. The data from each module is organized by the SSP's into a buffer, complete with headers containing word counts and status words for each module.

(5) When all SSP's on the cable segment have completed their device readouts, SSP0 reads the formatted data and appends this data to its own buffer, making a single buffer containing the data from all devices read out by all the SSP's. This, together with
an additional header containing run, date, time, tape number and total word count information forms an event buffer. Several events can be (and usually are) formed into a bigger buffer for efficiency in data block transfers. These multi-event buffers contain a header with run information as well as a pointer list to the beginning of each event buffer. Each multi-event SSP buffer is written to the FASTBUS memory.

(6) At the end of each event, SSP0 re-enables triggers from the fast trigger logic and goes back to step 1.

(7) When SSP0 receives information that the end of the beam spill has occurred or the FASTBUS memory is full, it sets a flag in the FASTBUS memory indicating that the memory is ready to be read out by the VAX host. It then halts, waiting for the VAX to read out the memory and restart SSP0.

The system has been timed to record approximately 300 kilobytes per second with an accelerator cycle time of 3 seconds and a beam spill time of 1 second. Since the system does not read the FASTBUS memory during the beam spill, this transfer rate corresponds to an effective recording speed of 450 kilobytes per second. A. Saulys and R. Hackenburg are in charge of the MPS data-acquisition system.
3.2 Data Analysis

The data was analyzed using standard procedures, see Table 3.1 [53].

The offline data processing in E-810 was carried out in two stages. In the first stage, the main task was to unpack the TPC raw data which was the most time-consuming part. This part was done by A. Saulys and W. Love. They used the Fermilab ACP (Advanced Computer Program) [64,65] Multiprocessor system at BNL to process the TPC raw data and wrote all the reconstructed track and vertex data for each good event to a data summary tape (DST).

The reconstructed track information of each event was stored in a “track bank” which contains the number of global tracks in the event, the position and momentum vectors at the start and the end of each track, the track curvatures at the upstream and downstream ends in the x-z and y-z plane, the charge of the particle, and other information. The vertex information was stored in a “vertex bank” which has the number of vertex, the momentum vector of each track at each vertex, and the statistical and error information of the vertex. The DST also contained the raw ADC and TDC data of the TOF system for the TOF data analysis.

<table>
<thead>
<tr>
<th>Level</th>
<th>Task</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Preprocessing</td>
<td>decodes raw data tapes, finds spatial coordinates</td>
</tr>
<tr>
<td>2</td>
<td>Pattern recognition</td>
<td>finds tracks, rough momentum with approximate field</td>
</tr>
<tr>
<td>3</td>
<td>Geometrical fitting</td>
<td>best track parameters using true field</td>
</tr>
<tr>
<td>4</td>
<td>Vertexing</td>
<td>associates tracks, particle decays</td>
</tr>
<tr>
<td>5</td>
<td>Kinematic fitting</td>
<td>assigns masses, finds missing neutrals</td>
</tr>
<tr>
<td>6</td>
<td>Physics analysis</td>
<td>finds effective masses, momentum spectra, etc.</td>
</tr>
</tbody>
</table>

TABLE 3.1: Offline analysis chain
In the second stage, the MPS group used the DST’s to study the physics of the TPC data and we used them to analyze the TOF data. The data in the June, 1990 run with Si and W targets is listed in Appendix D.

The ACP system, developed in Fermilab, is a cost effective way to process high energy experimental data. Our system includes a host computer (VAX3600) and a farm of inexpensive 32-bit microprocessors (up to 32 Motorola 68020’s). In its simplest form, a master program in the host computer reads an event, allocates the event data to an available microprocessor (the “slave”), collects the results from the slave, and writes the results to tape. Each slave runs an identical analysis program. This parallel processing is possible since each event is quite independent of the other events.
3.3 The Time Projection Chamber Data

With the TPC data alone, i.e., without particle identification (PID), we can determine pseudorapidities, reconstruct neutral V's (e.g., $K^0$, $\Lambda$, or $\bar{\Lambda}$), and have momentum information on both positive and negative particles in the same event. To a first approximation, we can assume all of the negative particles are pions. Of course there will be a few percent contamination of $K^-$, $\bar{p}$, $\mu^-$, and $e^-$, but for most practical purposes treating the negative particles as pions will suffice. Because the silicon nucleus has an equal number of protons (uud) and neutrons (udd), we can assume that the production probabilities of $\pi^+(u\bar{d})$ and $\pi^-(\bar{u}d)$ are equal. Then we can get the proton rapidity spectrum by histogramming the rapidity of all positive tracks as if they were protons and all negative tracks as if they were antiprotons and then subtracting the negatives from the positives bin by bin. Most importantly, we have to get the tracks first.

3.3.1 The TPC Pattern Recognition

The TPC pattern recognition program is written by Tom Morris. The TPC track recognition program consists of three parts: local pattern recognition (LPR) which associates contiguous readouts on adjacent wires to form a single hit, a subroutine which partitions the hits into slices in the y coordinate, and the track reconstruction part.

Local pattern recognition attempts to reconstruct, from the raw TPC readouts, the best set of coordinates representing the intercepts of tracks with each TPC row. LPR attempts to combine readouts on contiguous wires which overlap in time, and to ensure there is one hit per track, while at the same time optimizing the two-track resolution. These are competing goals since for optimum track reconstruction, it is desirable to combine readouts
that result from the breakup of clusters, but not clusters that come from different tracks. A cluster is defined to be a single readout on one wire.

The TPC is partitioned into slices in the $y$-$z$ projection whose vertices are at the target. The slices are approximately 1.0 cm high near $y = 0$ and 5.0 cm high at the top and bottom. The hits are indexed by slice number in each wire row, and the track recognition program normally searches for hits only within a single slice.

Track recognition is the most difficult problem in the analysis of the TPC data. It begins with a single hit at the downstream end of the last TPC module and works upstream. When three hits on adjacent rows can be spatially associated in three dimensions, a track is initialized. The track is then developed upstream from row to row within one module by local association in three dimensions. Absence of hits in two consecutive rows or two or more hit candidates in the same row terminates this stage of track development. When hits are assigned to a track, they are tagged to prevent their being reused.

In the next stage, circular least square fits are performed in the $x$-$z$ views and linear least square fits are performed in the $y$-$z$ views. If the fits are successful, the fitted orbit is extended over missing rows and to adjacent modules, and consistent hits are added to the track. If the fitting fails, there is provision for seeking out and discarding bad hits.

When the program completes one track, it moves on to the next hit and begins again. When the hits in the most downstream TPC row are exhausted, it moves to the next row upstream. The process continues until an attempt has been made to initialize a track with every previously unused hit. Finally, an attempt is made to join non-overlapping track segments. Three views of the TPC data after track recognition from a typical event are
FIG. 3.2: Three views of TPC tracks from a typical event
shown in Fig. 3.2 [66].

3.3.2 The TPC Vertex Search

After track reconstruction, the program searches for vertices. First it reconstructs a production vertex. It projects track orbits to the z of the target and then checks the x and y positions. Only orbits within cuts are accepted for vertexing. The position of a reconstructed production vertex must lie within the target area, i.e., $-5 \text{ cm} < x < 5 \text{ cm}$ and $-4 \text{ cm} < y < 4 \text{ cm}$. The z tolerance is $\pm 0.5 \text{ cm}$.

Next it looks for decay vertices from tracks whose orbits miss the production vertex. In order to reduce the combinatorial background of apparent $V^0$ decays, the following cuts were imposed:

1. Candidate decay tracks, projected to the primary production vertex, had to miss that vertex by at least 0.7 cm.

2. The decay point had to be at least 10 cm downstream of the production point.

3. The $V^0$ momentum vector had to point to the production vertex within a cut which varied from 0.3 to 0.6 cm, depending on the decay distance.

All $V^0$'s passing the above cuts were computed for $K^0(\pi^+\pi^-)$, $\Lambda(\pi^-p)$, and $\bar{\Lambda}(\pi^+\bar{p})$ invariant masses. Effective masses in the range of $1.106 < m(\pi^-p) < 1.126 \text{ GeV}/c^2$ were selected as $\Lambda$s. Effective masses in the range of $0.475 < m(\pi^+\pi^-) < 0.525 \text{ GeV}/c^2$ were selected as $K^0_s$'s. No significant $\bar{\Lambda}$ signal was observed. The effective mass spectra for $m(\pi^-p)$ and $m(\pi^+\pi^-)$ are shown in Fig. 3.3 [67].
FIG. 3.3: Effective mass spectra for $V^0_s$
3.4 The Time-of-Flight Data

Particle identification (PID) can be made by kinematics alone for $K^0$, $\Lambda$, and $\bar{\Lambda}$ from decay vertices as mentioned in the last section. If we want to study particle spectra from production vertices, e.g., $K/\pi$, $d/p$ ratios, then we need to find some way to provide PID. The time-of-flight method is a commonly used technique for PID. We have track momentum from the TPC data. If we know the velocity of the track, then we can determine the mass. To get the velocity of a track reaching the TOF hodoscope, we need to know two things, its path length and its flight time.

3.4.1 Time-of-Flight Method

From each PMT in the TOF paddle, as explained in the section of the TOF electronics, we took the anode and the dynode output signals. The anode signal was recorded in a LRS-2249 ADC to use for slew correction and the dynode signal in a LRS-2228 TDC for timing. The time information, $t_{idc}$, from a TDC was common started from the trigger and stopped by a dynode signal. The pulse height, or integrated charge, $q$, from an ADC was common gated by the trigger.

In order to get the true time interval, $t_{true}$, we need to determine the time offset of each tube, $t_0$, and the slew, or time-walk, correction from the pulse height, $t_{slew}$.

$$t_{true} = t_{idc} + t_0 + t_{slew} \quad (3.1)$$

The time interval, $\Delta t$, is defined as the time difference between $t_{true}$ of each PMT and $\bar{t}_{front}$ of the TOF front counter.

$$\Delta t = t_{true} - \bar{t}_{front} \quad (3.2)$$
where $i_{\text{front}}$ is defined as the mean time of the two true time intervals of the TOF front PMT's.

$$i_{\text{front}} = (t_{f3e,\text{true}} + t_{f3w,\text{true}})/2$$  \hspace{1cm} (3.3)

Equation 3.2 ensures the cancellation of the time jitter of the common start signal from the trigger. The time interval $\Delta t$ defined by equation 3.2 is related to the true flight time, $\tau$, of the particle between the TOF front counter and the TOF paddle by

$$\tau = (\Delta t_{\text{top}} + \Delta t_{\text{bottom}})/2 ,$$  \hspace{1cm} (3.4)

where the subscripts, top and bottom, are the top and bottom PMT's of the same paddle. The hit position $y$ is determined by

$$y = v_{\text{eff}} \cdot (\Delta t_{\text{bottom}} - \Delta t_{\text{top}})/2 ,$$  \hspace{1cm} (3.5)

where $v_{\text{eff}}$ is the effective velocity of light traveling up or down the scintillator.

Once we have the hit position, we can calculate the path length of the particle. The path length is composed of two parts, one inside the magnetic field calculated by track curvature and the other one outside the field calculated by linear extrapolation from the end of the field to the hit position.

### 3.4.2 Time-Walk Correction

This is the most important part of the correction if we want to reach sub-nanosecond time resolution. The formula we used for time-walk correction is shown below. See Appendix E for the derivation [68].

$$t_{\text{slew}} = t_c - t_{\text{dc}} = w(1/\sqrt{q_0} - 1/\sqrt{q})$$  \hspace{1cm} (3.6)
where $q_0$ is the integrated charge of a reference pulse, $w$ is a parameter determined by the risetime of the PMT and adjusted by data.

We examined the raw ADC distributions from each tube as shown in Fig. 3.4 and picked the center of the peak from hit particles as the reference point, $q_0$. In order to see the hit data, we set the scale to 200 counts in the figures to cut the pedestal peak. The signal peak varied from tube to tube, even from the same paddle. Therefore it is necessary to adjust the $q_0$, tube by tube. We also set a minimum cut for the ADC minus pedestal of each tube to cut the noise and background.

The coefficient $w$ should be adjusted tube by tube, but we had only about a few hundred counts per paddle per run. Therefore we assumed that it was a constant for all the tubes and was determined by the slew correction distribution as shown in Fig. 3.5. The criterion to determine $w$ was that the correction between the largest and the smallest pulses should be within the rise time of the tube. We chose $w$ to be 16.4 and the correction range was about 1.2 ns.

### 3.4.3 The Effective Velocity of Light in the Paddle

To determine the hit position, $y$, we need to know the effective velocity. The effective velocity of light, $v_{\text{eff}}$, traveling up or down the scintillator can be estimated by the critical angle, $\theta_c$, given by

$$\sin\theta_c = n_0 / n ,$$

(3.7)

where $n$ ($n_0$) is the index of refraction for the medium in (outside of) which the light is traveling. We take the outside medium to be air and $n$ to be 1.58, a typical value for plastic scintillator. The angle $\theta_c$ is $39.27^\circ$ measured with respect to the normal to the surface, so
FIG. 3.4: Raw ADC distributions from two paddles
FIG. 3.5: The slew correction distribution of the square-root formula.
that the range of \( v_{\text{eff}} \) is between 12 (light travels at angle \( \theta_c \)) and 19 (light travels directly to the light guide) cm/ns.

We determined \( v_{\text{eff}} \) by the distribution of the time difference of \( t_{\text{top}} \) and \( t_{\text{bottom}} \) shown in Fig. 3.6. Again we assumed it to be a constant for all paddles. The length of the paddle is 6 feet and the largest time difference between top and bottom is about 12.25 ns. Therefore we obtained a \( v_{\text{eff}} \) of about 14.4 cm/ns.

3.4.4 The Time Offset Calibrations

We set \( t_0 \) for each paddle such that the time difference between the paddle and the front counter equals the TOF of beam particles from the front counter to the target plus the TOF of production particles from the target to the hodoscope. The best way to achieve this is from a known TOF. If we assume all negative particles are pions, we can use the momentum information from the MPS to get the velocity of pions. We used negative particles with velocity above 0.999c to determine \( t_0 \).

The \( t_0 \) distributions of four paddles are shown in Fig. 3.7. We can use this method only when we have the path length of the particles reaching the hodoscope. To determine the \( t_0 \) of each tube of a paddle, we need to check the y distribution of the hit positions as shown in Fig. 3.8. The correct \( t_0 \) for each tube of a paddle will center the y distribution of the hits at \( y=0 \) position of that paddle.
FIG. 3.6: TDC difference distribution from the top and bottom tubes
FIG. 3.7: $T_0$ distributions of four paddles
FIG. 3.8: Y distributions of four paddles
3.4.5 Time Resolution of the TOF Hodoscope

We calculated the beta distribution of particles from the MPS by the pathlength and the TOF data. We assumed that they were all pions and selected negative particles with beta $> 0.999$. For the Gaussian fitting of the beta peak, the beta distribution has a standard deviation, $\sigma$ or RMS of 0.00252, as shown in Fig. 3.9. The pathlength from the target to the hodoscope is about 45 feet. Therefore the RMS time resolution is

$$\sigma_t = 120 \text{ ps}.$$
FIG. 3.9: The TOF $\beta$ spectrum for negative particles from Si-Si interactions
3.5 Acceptance Calculation

To understand the normalization for the data collected in the experiment, we need to do the acceptance calculation. This is usually done by generating events using Monte Carlo techniques and then propagating the generated particles through a simulation of the experimental apparatus and generating simulated raw data. We get the geometric acceptance of the apparatus, then we use the analysis program to analyze the simulated data to get the reconstruction efficiency. We used the HIJET event generator to generate events and GEANT3 to simulate the experimental apparatus.

3.5.1 HIJET Event Generator

HIJET [59,60] is a Monte Carlo event generator for p-nucleus and nucleus-nucleus collisions at relativistic energies. HIJET considers p-A and A-A collisions to be a sum of independent N-N collisions, with the N-N cross section and scattering dynamics not dependent on whether the nucleon has previously participated in an interaction. For each primary N-N interaction, a call is made to the MINBIAS routine of the program ISAJET. ISAJET [61] is an event generator for high energy N-N interactions. MINBIAS computes the energy loss of the colliding nucleons and production of particles. MINBIAS is based on inclusive high energy N-N interaction forming multi-pomeron chains. Each chain fragments according to the Field-Feynman algorithm [62].

HIJET allows projectile nucleons to successively traverse the target nucleus. A Woods-Saxon, or spherical distribution of nucleons is used, with a hard core repulsion. An option for nuclear Fermi motion exists. When the distance of closest approach with a target nucleon is within the radius of $\sigma (pp) \approx 33$ mb, an interaction is defined. ISAJET is then called. The
produced particles are transformed back to the target frame. The forward leading baryon continues to traverse the target nucleus until it exits, and the backward leading baryon is returned to the target array.

All generations of secondaries are considered. Secondary interactions are performed for both the target and projectile in a symmetric fashion. Cascading of struck nucleons from the target and projectile is allowed for. Secondaries produced in the collisions have a finite formation time given by the distribution

\[ F(\tau) \propto \exp(-\frac{\tau}{\tau_0 \cosh y}) \]  

where \( \tau_0 \) is the proper formation time and \( y \) is the rapidity of the produced particle in the target or projectile frame. \( \tau_0 \) is given by \( \tau_0 = \hbar F/\langle M_t \rangle \), where \( \langle M_t \rangle \) is the average transverse mass of the particles and \( F \) is a variable parameter which is adjusted to obtain the optimum formation time. The secondary particles materialize along the trajectory of the CM system of the parent particles. If a secondary is formed within the volume of either the target or the projectile nucleus, it may interact with nucleons in its path if the closest approach is less then \( \sqrt{\sigma_{mn}/\pi} \) where \( \sigma_{mn} \) is the total meson-nucleon cross section.

Near the threshold regions of \( \pi \)-nucleon and K-nucleon, an energy dependent cross section is used. An important peak in the \( \pi \)-nucleon cross section is \( \Delta \) formation, \( \pi N \rightarrow \Delta \). Delta formation is important for the mechanism of pion absorption. Once a secondary interacts, the forward leading meson continues to interact. The produced particles may re-interact depending on their formation time and trajectory.
3.5.2 The GEANT Detector Simulation System

GEANT is a large general purpose system of detector description, simulation, and graphical representation tools which was developed explicitly for High Energy Physics (HEP) experiments. The principal applications of GEANT are the tracking of particles through an experimental setup for acceptance studies or simulation of detector response, and the graphical representation of the setup and of the particle trajectories. The current version, GEANT3, was written in 1983. GEANT3 is a collection of FORTRAN77 routines, grouped together into several modules. For detail, see GEANT3 User Guide [63].

3.5.3 Monte Carlo Simulation of E-810 Data

The physics of the TPC detector and the response of the TPC readout electronics are simulated. Most of the TPC simulation and tracking packages were written by Tom Morris. The MPS group uses the CERN program GEANT3 to generate vertices, particle orbits, and coordinates of orbit intercepts of detectors. The simulated raw data is written out in Fastbus format.

The MPS simulation package does not create event kinematics, but rather reads a HIJET-generated kinematics file. The HIJET event files were created by R. Longacre and C.S. Chan. There are two output options: the Fastbus format mentioned above, and an image of the GEANT data structures after vertex, orbit, and detector-hit generation on each event. The latter file can also be read by the MPS package; thus the complete simulation can be done in two passes. This mode is convenient when studying the effects of changes in the TPC or electronics parameters, for example.

These simulated events were analysed by the same reconstruction program used for the
actual data in order to determine the acceptance and reconstruction efficiency of the TPC modules. In order to reduce the statistical errors, 100,000 simulated events were processed. This work was done by A. Saulys and W. Love.

3.5.4 Acceptance of the TOF Hodoscope

We used the HIJET event files and the DST's of the simulated events to calculate the acceptance of the TOF hodoscope. We extrapolated tracks which hit the last two rows of the third TPC module to the TOF hodoscope. Due to the long flight path, about 40 % of the pions and 20 % of the kaons decay before reaching the hodoscope. We stored the track information in a $p_T^2$ vs rapidity plot, since the differential cross-section for a particle of momentum $\vec{p}$ and energy $E$ is commonly written in a Lorentz invariant form,

$$E \frac{d^3\sigma}{d^3\vec{p}} = \frac{d^3\sigma}{dp_T^2 dy}.$$  \hspace{1cm} (3.9)

The geometric acceptance of the TOF system is shown in Fig. 3.10. In addition to the limited solid angle of the TOF hodoscope, the acceptance is limited by the momentum cuts on different particle species. The momentum cuts are due to the time resolution of the TOF system.

The DST’s of the simulated events already have included the TPC efficiency. The TPC efficiency of each pad, which consists of eight anode wires, is determined from data from the calibration runs. The calibration runs used a large size target 10 m upstream hit by a Si beam to generate a large number of secondary particles. These particles were almost parallel to the beam direction and went through the three TPC modules. From this data, we can estimate the efficiency of each pad. Due to the distortion of the field near the TPC
edges, we also put fiducial cuts on the x and y coordinates. The cuts were \(-15 \text{ cm} < y < 15 \text{ cm}\) and \(-29 \text{ cm} < x < 29 \text{ cm}\).

We compared the DST results with HIJET results and got a correction table in \(p_T^2\) vs \(y\). We used this table to correct the TOF raw data. The raw data and corrected results will be discussed in next chapter.
FIG. 3.10: Acceptance of the TOF hodoscope
Chapter IV

Results and Discussion

In the June, 1990 data taking run, the targets used were 1.2 mm silicon (Si) and 0.1 mm tungsten (W). The detailed run information is given in Appendix D. The TPC data, as shown in chapter I, can give the $\Lambda$ and $K^0$ production rates from the topology of neutral $V^0$ tracks and the pseudorapidity distributions for positively and negatively charged tracks. Assuming that all negative tracks are pions and positive tracks are pions plus protons, the rapidity distributions have been estimated for protons and negative pions.

Using the forward angle TOF data, we have measured the rapidity and $P_\perp$ distributions (albeit over a limited range of phase space) for $\pi^-$, $K^-$, $p$ (proton), and $d$ (deuteron). After cuts, mainly cuts from the veto counter $S_8$ and the position of the production vertex, 70k events from the Si target and 49k events from the W target corresponding to cross sections of 0.54 barns and 2.06 barns respectively were left for TOF data analysis. Thus the reaction was not limited to “central” events. A discussion on central collision in given in Appendix A.
4.1 Results from TOF Data

The results from the TOF data are shown in Figs. 4.1 to 4.10 and in Table 4.1. Plots of momentum versus beta for Si on Si for positive and negative tracks are shown in Figs. 4.1 and 4.2. Plots of momentum versus beta for Si on W for positive and negative tracks are shown in Figs. 4.3 and 4.4. The low momentum cutoff for the positive tracks is due to the offset of the TOF hodoscope to the left-hand side of the beam. The mass spectrum results from the Si target, calculated using the measured momentum and beta, are shown in Figs. 4.5 and 4.6. The mass spectrum results from the W target, calculated using the measured momentum and beta, are shown in Figs. 4.7 and 4.8. Clear signals for $\pi^-$, $K^-$, $p$ and $d$ are seen. Antiprotons ($\bar{p}$) are visible above the background, but there are too few to calculate $P_\perp$ distributions.

To calculate $P_\perp$ distributions for different kinds of particles, we have to do particle identification first. Using the mass plots (Figs. 4.5 to 4.8) for particle selections is not appropriate. The reason is the following, the mass of a particle is calculated by

$$\text{mass} = \frac{p}{\gamma \cdot \beta} = \frac{\sqrt{1 - \beta^2}}{\beta} \cdot p$$

(4.1)

where $p$ is momentum obtained from the curvature of the particle in the MPS and $\beta$ is calculated by the path length and flight time. The mass resolution is

$$\frac{dm}{m} = -\gamma^2 \cdot d\beta/\beta + dp/p$$

(4.2)

which is proportional to the TOF time resolution ($d\beta/\beta$) times $\gamma^2$ if we assume that the momentum error is zero. For the same momentum, a lighter particle has a bigger $\gamma$ and will have very poor mass resolution. This is especially true for pions. Therefore we use a
different approach to select particles. Using the kinematic relation between momentum and beta for a known mass, shown in Figs. 4.1 - 4.4 as solid lines, we identify particles within 4σ of the time resolution along these curves and set momentum cuts for pions and kaons at 2.5 GeV/c, protons at 5 GeV/c, and deuterons at 8.5 GeV/c.

The transverse momentum spectra after acceptance correction for π−, K−, p and d are shown in Fig. 4.9 for the Si target and Fig. 4.10 for the W target. The distributions, \( \frac{1}{N_{cw}} \frac{dN^2}{dm_\perp dy} \) are plotted as a function of the transverse kinetic energy

\[
T_\perp = m_\perp - m_0
\]  

(4.3)

where \( m_\perp = (P^2_\perp + m_0^2)^{1/2} \) is the transverse mass, \( P_\perp \) is the transverse momentum, and \( m_0 \) is the rest mass. The data has been fitted to the form \( A \exp(-T_\perp/T_0) \), where \( T_0 \) is the effective temperature parameter. These parameters for different particles are listed in Table 4.1 at rapidity range 1.9 < \( y < 2.1 \). We find that the measured effective temperature increases with increasing mass of the emitted particle.

By integrating the exponential equation, we can determine the value for \( dN/dy \) at rapidity range 1.9 < \( y < 2.1 \). The values are given in Table 4.1. These values must be viewed with caution because of the limited \( P_\perp \) range. The values for \( dN/dy \) increase with \( A \) as would be expected. Finally the production ratios for the \( K^-/\pi^- \) and \( d/p \) are also listed in Table 4.1. We will discuss these results in the following section.
TABLE 4.1: Effective temperatures and $dN/dy$

for $\pi^-$, $K^-$, $p$ and $d$ from Si-Si and Si-W collisions

at $1.9 < y < 2.1$. All errors are statistical only.

<table>
<thead>
<tr>
<th>Particle</th>
<th>$T_0$ (MeV)</th>
<th>$dN/\text{dy}$</th>
<th>$T_0$ (MeV)</th>
<th>$dN/\text{dy}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^-$</td>
<td>88 ± 1.4</td>
<td>19.5 ± 0.5</td>
<td>87 ± 1.6</td>
<td>26.6 ± 0.8</td>
</tr>
<tr>
<td>$K^-$</td>
<td>103 ± 10</td>
<td>0.52 ± 0.08</td>
<td>98 ± 5.5</td>
<td>0.65 ± 0.05</td>
</tr>
<tr>
<td>$p$</td>
<td>137 ± 7</td>
<td>17.1 ± 1.2</td>
<td>163 ± 10</td>
<td>22.9 ± 1.4</td>
</tr>
<tr>
<td>$d$</td>
<td>282 ± 48</td>
<td>0.6 ± 0.1</td>
<td>325 ± 73</td>
<td>0.89 ± 0.2</td>
</tr>
<tr>
<td>$K^-/\pi^-$</td>
<td>2.7 ± 0.3 %</td>
<td>2.4 ± 0.2 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$d/p$</td>
<td>3.5 ± 0.7 %</td>
<td>3.9 ± 0.9 %</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
MOENTUM vs BETA + Si

FIG. 4.1: Scatter plot of momentum vs beta + Si
FIG. 4.2: Scatter plot of momentum vs beta - Si
FIG. 4.3: Scatter plot of momentum vs beta + W
FIG. 4.4: Scatter plot of momentum vs beta - W
Si on Si: Positive Particles

Mass (GeV) with beta < 0.986

FIG. 4.5: Mass spectrum of positive particles from Si with $\beta < 0.986$
Si on Si : Negative Particles

Mass (GeV) with beta < 0.986

FIG. 4.6: Mass spectrum of negative particles from Si with $\beta < 0.986$
Si on W : Positive Particles

Mass spectrum of positive particles from W with $\beta < 0.986$
Si on W : Negative Particles

Mass spectrum of negative particles from W with $\beta < 0.986$

FIG. 4.8: Mass spectrum of negative particles from W with $\beta < 0.986$
FIG. 4.9: \((1/N_{ev}) \times dN^2/dm_{\perp}^2 \, dy \) vs \(T_{\perp} \) for \(\pi^-\), \(K^-\), \(p\), and \(d\) from Si
FIG. 4.10: $(1/N_{ev}) * dN^2/dm^2 dy$ vs $T_\perp$ for $\pi^-$, $K^-$, $p$, and $d$ from W
4.2 Discussion

The fitting of the transverse momentum distribution in an exponential form is based on a thermal or fireball model [69]. Assume that particle emission is isotropic with a thermal distribution:

\[ \frac{d^3n}{dp^3} = \frac{C}{e^{(E-\mu)/T} \pm 1} \]  \hspace{1cm} (4.4)

where the + sign is for fermions and the - sign for bosons. C is a constant and \( \mu \) is the chemical potential. Usually, the limit of a Maxwell-Boltzmann distribution is taken:

\[ \frac{d^3n}{dp^3} = Ae^{-E/T} \]  \hspace{1cm} (4.5)

where \( A = Ce^{\mu/T} \) is taken as a constant for each particle species. The total particle number of a given species, \( N \), is obtained by integrating \( d^3/dp^3 \) over momentum space.

\[ N = A \times 4\pi m^2TK_2(m/T) \]  \hspace{1cm} (4.6)

where \( K_2 \) is a modified Hankel function.

Empirically in p-p collisions the dependence on transverse momentum \( p_\perp \) of measured cross sections is generally well described by

\[ \frac{d\sigma}{dp_\perp^2} = Ae^{-Bm_\perp} \]  \hspace{1cm} (4.7)

Comparing it with the Maxwell-Boltzmann

\[ \frac{d\sigma}{dv_\perp^2} = Ae^{-E/kT} \]  \hspace{1cm} (4.8)

where \( T \) is the temperature of the system, \( \nu \) is a particle’s velocity, and \( E \) the particle’s energy. Hence the inverse slope \( 1/B \) (\( \propto \langle p_\perp \rangle \)) should be proportional to the system’s temperature.
4.2.1 Effective Temperature

The measured temperature in Table 4.1. increases with increasing mass of the emitted particle. In the thermal model, the value of $T_0$ must be the same for all kinds of particles, since they are emitted from a common thermal bath. However the measured temperature is different for different kinds of particles. In order to overcome this difficulty, Siemens and Rasmussen [70] proposed a model of a radially expanding flow. We take pions and protons as an example. They considered a spherically symmetric fireball expanding to a radial velocity $\beta$ and a temperature $T$ and assumed that pions are in kinetic equilibrium with the nucleons, attaining a common temperature $T$ and flow velocity $\beta$. For large $p$, the apparent temperature $T_{app}$ is as the following

$$T_{app} = \frac{T}{\gamma(1 - \frac{\beta E}{p})}$$

(4.9)

At a fixed momentum, the energy of a proton is much larger than the energy of a pion, because $m_p > m_\pi$ and $T_{app}(p) > T_{app}(\pi)$. In simple terms, at a fixed energy, the velocity of a proton is much smaller than the velocity of a pion. Therefore, if a radially expanding flow is superposed on the thermal spectra, the slower particles (protons) are influenced more by this flow than the faster particles (pions). In other words, there will be a greater enhancement in kinetic energy for protons then for pions.

A second model which tries to explain the difference in temperature, relates temperature to the phase space of individual $NN$ collisions. Therefore, the model is called a phase space model [73]. In order to produce pions, a 140 MeV rest-mass energy has to be created. Then, if the total energy is fixed, less kinetic energy is available for pions than for protons. This model predicts $T_0(\pi) < T_0(p)$, the same as above.
Now let us discuss the kaon spectra. Comparison of the value of $T_0$ for kaons with that for pions and protons will give us further insight into the production mechanism of these particles. If the radially expanding flow determines the slope difference, then we expect

$$ T_0(\pi) < T_0(K) < T_0(p), $$

(4.10)

since $m_\pi < m_K < m_p$. On the other hand, if the phase space of particle production determines the shape of the energy spectrum, we then expect

$$ T_0(K) < T_0(\pi) < T_0(p), $$

(4.11)

since the threshold energy of kaon production is much higher than that of pion production. The available kinetic energy for kaon is much less than that for pion.

Our experimental results can be explained by the radially expanding flow model. E802 finds that [38],

$$ T_0(\pi) < T_0(K^+) < T_0(p). $$

The $K^+$ production rate is much larger than the $K^-$ production rate. Therefore the $K^+$ measurement from E802 is better for effective temperature comparison between pions and kaons.

4.2.2 Kaon/pion Ratios

The $K^-/\pi^-$ ratio from our results is $(2.7 \pm 0.3)$ % for the Si target and $(2.4 \pm 0.2)$ % for the W target in the rapidity interval $1.9 < y < 2.1$.

For the pion production, the E-810 results from the TPC data indicate that there is an excess of "soft" pions below a $T_\perp$ of 0.3 GeV as shown in Fig. 4.11 [71]. The limited $T_\perp$
range of the TOF data, 0.1 - 0.25 Gev, results in a lower temperature for pions. The pion excess was explained by a HIJET model that included enhanced $\Delta$ production, which gives rise to an enhancement of the pion spectrum below $T_\perp = 0.3$, and Coulomb interactions with the co-moving charged matter, which increase the pion spectrum at the lowest values of $T_\perp$. If the pion enhancement is taken into account, our $K^-/\pi^-$ ratio values are consistent with E-802 results, $(3.3 \pm 0.5)\%$. The $K^-/\pi^-$ ratio for $pp$ collisions at the same rapidity is $\approx (2.4 \pm 2.0)\%$, the large uncertainty arising from the low yield of $K^-$. Because of this large uncertainty, one cannot determine whether this ratio is different in heavy-ion collisions.

Since the MPS magnet bent positive particles away from the TOF hodoscope, the momenta of positive particles reaching the TOF hodoscope are above 3 GeV/c as shown in the scatter plot. Our time resolution can separate kaons from pions only below 2.5 GeV/c. Therefore we do not have $K^+/\pi^+$ results. However the $K^+/\pi^+$ ratio from E-802 is $(19.2 \pm 3)\%$, which is much larger than the corresponding ratio of $(4 - 8)\%$ measured in $pp$ reactions. Analysis of data for $pA$ collisions indicates a $K^+/\pi^+$ ratio that is intermediate between the $pp$ and Si+Au results, albeit for a somewhat different kinematic range. An enhancement of $K^+$ production, called the $K^+$ distillation effect [72], has been predicted to occur if either very high baryon density matter or a quark-gluon plasma is formed. However, other mechanisms from hadronic interactions are also possible. For example, the re-scattering of the reaction products, $\pi^+n \to K^+\Lambda$, could provide a mechanism for the $K^+$ enhancement.
4.2.3 Composite Particle Formation

Now, let us study the formation of composite fragments, such as $d$, $t$, $^3He$, etc [74]. Naively we expect that the probability of forming a deuteron at a velocity $\vec{v}_d$ is proportional to the product of the probabilities of finding a proton and a neutron at the same velocity:

$$p_d(\vec{v} = \vec{v}_d) \propto p_p(\vec{v} = \vec{v}_d) \cdot p_n(\vec{v} = \vec{v}_d). \quad (4.12)$$

If the neutron spectra can be approximated by the proton spectra, then we expect the cross section of a composite fragment with mass number $A$ to be given by,

$$E_A(d^3\sigma_A/dp_A^3) = C_A \cdot ((E_p(d^3\sigma_p/dp_p^3))^A, \quad (4.13)$$

where $p_A$ equals $A \cdot p_p$, and $C_A$ is a constant. This is called the coalescence model [75,76]. Nucleons stick together through final state interactions to form composite fragments. Dover et al., [77] developed a relativistic covariant coalescence model to simulate $Si$ on $Au$ at $14.6 \times A$ GeV/c. They predict $dN_d/dy \simeq 0.8$ at $y = 1.1$. Our $dN_d/dy$ from $W$ is $0.89 \pm 0.2$ which is consistent with the model.
FIG. 4.11: Ratio of transverse momentum spectra to a reference exponential
Chapter V
Summary

Experiment E-810 has measured the central collisions of Si ions at 14.6 GeV/n on various targets at the Brookhaven AGS using the Multiparticle Spectrometer. The trajectories and momentum of charged particles in the forward hemisphere in the CM system or from $0^\circ$ to $20^\circ$ in the lab system were measured using three TPC modules in a 5 kG magnetic field.

A 32 element TOF hodoscope was positioned 13.5 m from the target and offset to the left of the beamline. The hodoscope accepted a $p_t$ range of $0.0 < p_t < 0.5$ GeV/c for negative particles and $0.5 < p_t < 1.2$ GeV/c for positive particles. With a time resolution of $\sigma = 120$ ps and a flight path of 13.5 m, we achieved good kaon to pion separation up to 2.5 GeV/c, kaon to proton separation up to 5 GeV/c, and deuteron to proton separation up to 8.5 GeV/c. Due to the small acceptance of the hodoscope, we measured the momentum spectra of $\pi^-$, $K^-$, p and d over a limited range of rapidity, $1.9 < y < 2.1$.

From the TOF results, we find that the inverse slope parameters $T_0$ obtained by an exponential fit with the transverse mass spectra in transverse kinetic energy are

$$T_0(\pi) < T_0(K) < T_0(p) < T_0(d)$$

which is predicted by a radially expanding flow model. By integrating the exponential equation, we can determine the $dN/dy$ value for the rapidity range, $1.9 < y < 2.1$. From the integrated results, we find that the $K^-/\pi^-$ ratios, $(2.7 \pm 0.3)$ % from the Si target and
(2.4 ± 0.2) % from the W target, are consistent with pp collision results, (2.4 ± 2.0) %. The deuteron production rates can be explained by a relativistic coalescence model.

There was no indication of the QGP in our results. The CM energy is only 5.4 GeV/n and Si ion is really not a heavy ion. Therefore, these results are not unexpected.
Appendix A

Units and Variables

Units

Cross section

Nuclear cross sections, which have the dimensions of area, are commonly measured in barns.

\[ 1 \text{ } b = 10^{-28} \text{ } m^2 = 100 \text{ } fm^2 \]

where \( 1 \text{ } fm = 10^{-15} \text{ } m \).

Temperature and energy

Their relationship is given by the Boltzmann constant, \( k_B \),

\[ k_B = 1.38 \times 10^{-16} \text{erg/K} = 8.625 \times 10^{-11} \text{MeV/K} \]

\[ \Rightarrow 100 \text{MeV} \approx 1.2 \times 10^{12} \text{K} \]

\( \hbar c \approx 197 \text{MeV fm} \).

Variables

Rapidity

The rapidity of a particle has the following physical meaning: find a reference system moving with the z axis parallel to \( p_L \) in which the particle has only transverse momentum. This system moves with velocity \( \beta \) with respect to the lab. Then

\[ y \equiv \tanh^{-1} \beta \quad (A.1) \]
is the rapidity of the particle with respect to the lab. Some important relations between
rapidity and other variables are given below:

\[ y = \tanh^{-1} \frac{p_L}{E} = \frac{1}{2} \ln \frac{E + p_L}{E - p_L} = \ln \frac{E + p_L}{E_T} \]  \hspace{1cm} (A.2)

\[ \gamma = (1 - \beta^2)^{-1/2} = \cosh y \]  \hspace{1cm} (A.3)

\[ \gamma \beta = \sinh y \]  \hspace{1cm} (A.4)

\[ p_L = m_T \sinh y \]  \hspace{1cm} (A.5)

\[ E = m_T \cosh y \]  \hspace{1cm} (A.6)

where \( E \) is particle’s energy and \( p_L \) is particle’s longitudinal momentum.

**Rapidity of the CM system in the Lab system**

The total energy in the CMS is \( \sqrt{s} \). The energy and momentum of the CMS in the LS are
\( \gamma \sqrt{s} \) and \( \beta \gamma \sqrt{s} \), respectively. The rapidity of the CMS in the LS is

\[ y_{cm} = \frac{1}{2} \ln \frac{\gamma \sqrt{s} + \beta \gamma \sqrt{s}}{\gamma \sqrt{s} - \beta \gamma \sqrt{s}} = \frac{1}{2} \ln \frac{1 + \beta}{1 - \beta}. \]  \hspace{1cm} (A.7)

**Lorentz transformation of the rapidity of a particle**

The rapidities of a particle in two different coordinate systems, \( S \) and \( S' \) with relative
velocity \( \beta \), are

\[ y = \frac{1}{2} \ln \frac{E + p_L}{E - p_L} \]

and

\[ y = \frac{1}{2} \ln \frac{E' + p'_L}{E' - p'_L} \]

Making Lorentz transformation on the \( E \) and \( p_L \)

\[ y = \frac{1}{2} \ln \frac{\gamma (E' + \beta p'_L) + \gamma (\beta E' + p'_L)}{\gamma (E' + \beta p'_L) - \gamma (\beta E' + p'_L)} \]
\[
\frac{1}{2} \ln \frac{E' + p_L'}{E' - p_L'} + \frac{1}{2} \ln \frac{1 + \beta}{1 - \beta}.
\]

or

\[
y = y' + y_\beta
\]

where \(y_\beta\) is a constant. This is a very important property of the rapidity. It means that the shape of the rapidity distribution is invariant under a Lorentz transformation.

**Rapidity interval and incident energy**

In high energy beams, \(\sqrt{s} \gg m_p, m_t\) and \(p_L \approx E_p\)

\[
\Delta y = y_p - y_t = \ln \frac{E_p + p_L}{E_p T} - 0
\]

\[
\Delta y \approx \ln \frac{s}{m_p m_t}
\]

(A.9)

where \(p\) denotes projectile and \(t\) denotes target. In pp collisions,

\[
\Delta y \approx \ln \frac{s}{m_N^2}
\]

(A.10)

At AGS energy, 14.6 GeV/n, \(\Delta y \approx 3.4\).

At SPS energy, 100 GeV/n, \(\Delta y \approx 5.3\).

**Pseudorapidity**

In relativistic case, \(E \approx pc\), we get

\[
y \approx \frac{1}{2} \ln \frac{p + p_L}{p - p_L} \approx \frac{1}{2} \ln \frac{1 + \cos \theta}{1 - \cos \theta} \approx -\ln \frac{\tan \frac{\theta}{2}}{2}
\]

(A.11)

The function

\[
-\ln \frac{\tan \frac{\theta}{2}}{2}
\]

(A.12)

is called pseudorapidity and is usually represented by \(\eta\). The pseudorapidity is a very convenient variable, because it depends only on the angle \(\theta\). For example, in nuclear emulsion
experiments, we have no information of particle's ID and momentum, except the emission angle.

**Invariant mass**

In a fixed target experiment, an incident particle with momentum $\vec{P}_1$, energy $E_1$, and mass $m_1$ collides with a particle with mass $m_2$, at rest. In the Lab system, the four vectors are

$$p_1 = (\vec{P}_1, E_1), \quad p_2 = (0, m_2)$$

In the CM system, the four vectors are

$$p_1^* = (\vec{P}_1^*, E_1^*), \quad p_2^* = (-\vec{P}_2^*, E_2^*)$$

The modulus of the total four-momentum is a Lorentz invariant quantity, which is the same in all reference systems.

$$-s \equiv (p_1 + p_2)^2 = -(E_1^* + E_2^*)^2$$

It is clear that $\sqrt{s}$ is the total energy in the CM system, which is the same as the invariant mass of the CM system. In terms of the lab quantities,

$$s = m_1^2 + m_2^2 + 2E_1m_2 \quad \text{(A.13)}$$

**Transverse mass**

$$m_T = m_\perp = \sqrt{m^2 + p_T^2} \quad \text{(A.14)}$$

where $m$ is rest mass and $p_T$ is the transverse momentum.

**Transverse kinetic energy**

$$T_T = T_\perp = m_T - m \quad \text{(A.15)}$$
\( E_T \): Transverse energy

The transverse energy \( E_T \) is defined as the sum over final particles

\[
E_T \equiv \sum_i E_i \sin \theta_i
\]  
(A.16)

where \( E_i \) and \( \theta_i \) are the energies and angles of the emerging particles.

Nucleon mean free path

\[
l_N \simeq \frac{1}{n_0 \sigma_{NN}} = 1.7 \, fm
\]

where \( \sigma_{NN} \) is \( NN \) cross section and \( n_0 = 0.17 \, fm^{-3} \) is the typical nuclear density.

Inclusive reactions [78]

Reactions involving only few final particles, in which all final particles are measured, are termed exclusive reactions. Collisions at high energies generally involve the production of many particles. For example, the Si on W interactions in our experiment, the measured charge multiplicities are range from 10 to 100. To study this kind of reactions, a complementary approach called inclusive reaction is adopted. An inclusive experiment measures the probability for the production of a specified configuration of particles in a collision, independent of whatever else might be produced.

A single-particle inclusive reaction, in which the cross section for the production of particle C is measured regardless of whatever is produced along with C,

\[
\text{beam + target } \rightarrow \text{C + anything}
\]  
(A.17)

is commonly used. A single-particle inclusive reaction is characterized by a function, \( E d\sigma/d^3p \), which is proportional to the probability for emitting particle C, of momentum \( \vec{p} \) and energy \( E \), into a Lorentz-invariant differential element of momentum space \( d^3p/E \).
Normal nuclear density

The density of nucleons in normal nuclear matter is

\[ \rho_0 = \frac{A}{V} = \frac{A}{\frac{4}{3}\pi R^3} \approx 0.17 \, \text{fm}^{-3} \]  \hspace{1cm} (A.18)

where \( R \approx 1.2 \, A^{1/3} \) fm.

Central collisions

In central collisions, by definition, the impact parameter, \( b \), equals zero, but usually we use

\[ b \leq 1 \, \text{fm} \]  \hspace{1cm} (A.19)

for central collisions, \( \text{i.e.} \sigma \approx 0.03 \) barns.

From purely geometrical considerations,

\[ \frac{\sigma_{\text{central}}}{\sigma_{\text{total}}} \sim \left( \frac{1}{R_{\text{proj}} + R_{\text{target}}} \right)^2 \approx \frac{1}{(1.2(A_p^{1/3} + A_t^{1/3}))^2} \]  \hspace{1cm} (A.20)

For \(^{28}\text{Si}\) on \(^{28}\text{Si}\), we get

\[ \sigma_{\text{central}}/\sigma_{\text{total}} \sim 0.02 \]

and \( \sigma_{\text{total}} \sim 4\pi R^2 \approx 1.63 \) barns.

For \(^{28}\text{Si}\) on \(^{183}\text{W}\), we get

\[ \sigma_{\text{central}}/\sigma_{\text{total}} \sim 0.01 \]

and \( \sigma_{\text{total}} \approx 3.46 \) barns. If the two nuclei have different radii, the smaller one makes a hole in the larger and all nucleons of the smaller can participate in the reaction.

Peripheral collisions

In peripheral collisions, the two nuclei only partially overlap as compared to central collisions.
Coherent and incoherent interactions

Coherent interactions are interactions where each nucleus interacts as a whole; there is a collective effect of the nucleons. On the other hand, the incoherent collision is a succession of independent nucleon-nucleon interactions; there is no collective effect.

**Bjorken model to estimate the energy density** [79,69]

In the collision of two identical nuclei of radius R, consider a slice in rapidity space of thickness $\Delta y$ and let $N$ be the number of particles contained in this slice and $\langle E \rangle$ the average energy of the $N$ particles. The energy $E$ contained in the slice is

$$ E = N \frac{d\langle E \rangle}{dy} \Delta y $$

Let us consider a volume $V$ determined by $\Delta y$ and the area of the nuclei transverse to the rapidity, at a proper time $\tau$

$$ V = \tau \Delta y \pi R^2 $$

The energy density is

$$ \epsilon = \frac{E}{V} = N \frac{1}{\tau \pi R^2} \frac{d\langle E \rangle}{dy} \quad (A.21) $$

which is Bjorken’s estimate.

An interesting approximation can be made for the central region. In this region the longitudinal momenta are small and the following approximation holds

$$ N \frac{d\langle E \rangle}{dy} \approx \frac{dN}{dy} \langle M_T \rangle \quad (A.22) $$

where $\langle M_T \rangle$ is the average transverse mass of the secondary hadrons. Therefore, the energy density is

$$ \epsilon \approx \frac{dN}{dy} \frac{\langle M_T \rangle}{\tau \pi R^2} \quad (A.23) $$
which is Bjorken’s estimate for the central region. In this region, the energy density is proportional to the rapidity distribution of the secondary hadrons.

**Landau model to estimate the energy density**

Consider two nuclei approaching each other with CM energies $1/2E_{cm}$. They are Lorentz contracted to a longitudinal size $2R_A/\gamma$, where $R_A \approx A^{1/3}$ is the nuclear radius and the Lorentz factor $\gamma$ is equal to $E_{cm}/2m_N A$. After collision, they come to rest in the CM frame concentrating $E_{cm}$ energy in a volume $V = (2R_A/\gamma)R_A^2$. This energy density, $\rho$, is

$$\rho \equiv \frac{E_{cm}}{V} \approx \gamma^2 (m_N n_0),$$  \hspace{1cm} (A.24)

where $n_0$ is the baryon number density of normal nucleus. For ultra-relativistic ions, the Landau model is not valid. It leads to too high energy densities.
Appendix B

The Four Basic Forces and Elementary Particles

The Four Basic Forces [9,81]

There are four basic forces which act among elementary particles, shown in Table B.1. The gravitational and electromagnetic forces, which have infinite ranges, were already known from classical physics. The strong or nuclear force is the strongest of the four forces. It holds the nucleus together and also holds the hadrons together and is limited to a range of about $10^{-13}$ cm. Lastly, the weak force which is responsible for radioactive $\beta$-decay has an even shorter range, $<10^{-16}$cm. The last two forces are short range and not felt directly in everyday life. That is why they were not found until this century.

The long-range electromagnetic and short-range weak forces, although they are strikingly different, are believed to be low energy manifestations of one and the same force,

<table>
<thead>
<tr>
<th>Type of force</th>
<th>Interaction range</th>
<th>Relative strength</th>
<th>Force carrier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong or nuclear force</td>
<td>$\leq 10^{-13}$ cm</td>
<td>1</td>
<td>Gluon</td>
</tr>
<tr>
<td>Electromagnetic force</td>
<td>Infinite</td>
<td>$10^{-2}$</td>
<td>Photon</td>
</tr>
<tr>
<td>Weak force</td>
<td>$\leq 10^{-16}$ cm</td>
<td>$10^{-13}$</td>
<td>$W^+, W^-, and Z^0$</td>
</tr>
<tr>
<td>Gravitational force</td>
<td>Infinite</td>
<td>$10^{-38}$</td>
<td>Graviton</td>
</tr>
</tbody>
</table>

TABLE B.1: The four basic forces
called the "electroweak force". The unified electroweak theory by Weinberg (1967) [80] and Salam (1968) and was confirmed by later experiments, a triumph of particle physics.

At the nuclear scale, $10^{-13}$ cm, the gravitational force is negligible compared to the other forces. The difference in strength is more than a factor of $10^{38}$ between the strong and gravitational forces as shown in Table B.1.

**Elementary Particles [9,81]**

We can classify the elementary particles according to the type of force they feel. All of the known elementary particles are subject to gravitational and weak forces. Hadrons, e.g. protons, neutrons, and pions, are particles participating in the strong force. Integral-spin hadrons are called mesons and half-integral-spin hadrons are called baryons. The number of known hadrons is a few hundred. Most of them are extremely unstable and called resonances which decay into lighter hadrons through the strong force in less then $10^{-21}$ seconds. Particles that are not influenced by the strong force are called leptons, i.e., $e$, $\nu_e$, $\mu$, $\nu_\mu$, $\tau$, and $\nu_\tau$.

All hadrons and leptons, apart from the neutrinos, are subject to electromagnetic force. Note that even neutral hadrons like neutron, feel the electromagnetic force, for example, through their charge distribution or their magnetic moment.

It is currently believed that all hadrons are made of quarks, which have six different flavors, i.e., $u$, $d$, $c$, $s$, $t$, and $b$. Each flavor has three different colors. Baryons are made up of three quarks and mesons of a quark and an antiquark. Some hadrons and their quark contents are listed in Table B.2.

According to the current view, the quarks and the leptons are the fundamental building blocks of matter. They are fermions, i.e., they have half-integral spin and obey Fermi-Dirac
statistics. We also need other fundamental particles called field particles, which are carriers of the forces between material particles. All the field particles are bosons, and obey Bose-Einstein statistics. The fundamental particles are listed in Table B.3.

<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>Mass (GeV)</th>
<th>Charge</th>
<th>Quark contents</th>
</tr>
</thead>
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<tr>
<td>Proton</td>
<td>p</td>
<td>0.938</td>
<td>+1</td>
<td>uud</td>
</tr>
<tr>
<td>Antiproton</td>
<td>\bar{p}</td>
<td>0.938</td>
<td>-1</td>
<td>\bar{u}\bar{d}</td>
</tr>
<tr>
<td>Neutron</td>
<td>n</td>
<td>0.940</td>
<td>0</td>
<td>udd</td>
</tr>
<tr>
<td>Antineutron</td>
<td>\bar{n}</td>
<td>0.940</td>
<td>0</td>
<td>\bar{u}\bar{d}\bar{d}</td>
</tr>
<tr>
<td>Positive pion</td>
<td>\pi^+</td>
<td>0.140</td>
<td>+1</td>
<td>ud</td>
</tr>
<tr>
<td>Negative pion</td>
<td>\pi^-</td>
<td>0.140</td>
<td>-1</td>
<td>\bar{u}\bar{d}</td>
</tr>
<tr>
<td>Neutral pion</td>
<td>\pi^0</td>
<td>0.135</td>
<td>0</td>
<td>u\bar{u}, \bar{d}\bar{d}</td>
</tr>
<tr>
<td>Positive kaon</td>
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<td>-1</td>
<td>\bar{u}s</td>
</tr>
<tr>
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<td>K^0</td>
<td>0.498</td>
<td>0</td>
<td>d\bar{s}, \bar{d}\bar{s}</td>
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<tr>
<td>D^+ charm meson</td>
<td>D^+</td>
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<td>+1</td>
<td>c\bar{d}</td>
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<td>D^-</td>
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<td>-1</td>
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<tr>
<td>D^0 charm meson</td>
<td>D^0</td>
<td>1.865</td>
<td>0</td>
<td>c\bar{u}, \bar{c}\bar{u}</td>
</tr>
<tr>
<td>Psi or J</td>
<td>\psi/J</td>
<td>3.097</td>
<td>0</td>
<td>c\bar{c}</td>
</tr>
<tr>
<td>Upsilon</td>
<td>\Upsilon</td>
<td>9.460</td>
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<td>b\bar{b}</td>
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TABLE B.2: Properties of some hadrons
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<td>$&lt; 1.8 \times 10^{-8}$</td>
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<tr>
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<td>$0.511 \times 10^{-3}$</td>
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<tr>
<td>Up quark</td>
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<td>$\frac{2}{3}$</td>
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<tr>
<td>Down quark</td>
<td>$d$</td>
<td>$-\frac{1}{3}$</td>
<td>0.35</td>
</tr>
<tr>
<td><strong>Generation II</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Muon neutrino</td>
<td>$\nu_\mu$</td>
<td>0</td>
<td>$&lt; 0.25 \times 10^{-3}$</td>
</tr>
<tr>
<td>Muon</td>
<td>$\mu$</td>
<td>-1</td>
<td>0.106</td>
</tr>
<tr>
<td>Charm quark</td>
<td>$c$</td>
<td>$\frac{2}{3}$</td>
<td>1.8</td>
</tr>
<tr>
<td>Strange quark</td>
<td>$s$</td>
<td>$-\frac{1}{3}$</td>
<td>0.55</td>
</tr>
<tr>
<td><strong>Generation III</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tau neutrino</td>
<td>$\nu_\tau$</td>
<td>0</td>
<td>$&lt; 0.035$</td>
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<tr>
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<td>$\tau$</td>
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<td>Top quark</td>
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<td>$&gt; 90(?)$</td>
</tr>
<tr>
<td>Bottom quark</td>
<td>$b$</td>
<td>$-\frac{1}{3}$</td>
<td>4.5</td>
</tr>
<tr>
<td><strong>Gauge Bosons</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
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<td>$\gamma$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>W boson</td>
<td>$W^{\pm}$</td>
<td>±1</td>
<td>82</td>
</tr>
<tr>
<td>Z boson</td>
<td>$Z^0$</td>
<td>0</td>
<td>93</td>
</tr>
<tr>
<td>Gluon</td>
<td>$g$</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**TABLE B.3:** The elementary particles
Appendix C

E810 System Logic

Format for the MPS control system drawings

The circuit module is given a number that serves as a geographic address. This address has five components;

Region- Electronics house, Control room, & Floor area symbolized by E, C, & F respectively.

Rack- Number marked on the top of each rack. It ranges from 01 to 99.

Crate- Position to the nearest foot of the lower edge of the crate. Note, NIM and CAMAC crates are about one foot high including the cooling fans.

Slot- Number of the slot marked on the crate or slot number counting from the left.

Channel- Circuits with multiple identical channels are labeled by letters starting with A for the top channel.

The total geographic address then is a letter (region), a two digit number (rack), a one digit number (crate), a two digit number (slot), and a one digit letter (channel) if relevant, all separated by commas.
The current Schema library contains drawings for the following

NIM and CAMAC modules:

### NIM

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>100</td>
<td>Joerger quad four fold and with veto</td>
</tr>
<tr>
<td>101</td>
<td>Joerger dual majority coinc.</td>
</tr>
<tr>
<td>222</td>
<td>LeCroy dual gate gen.</td>
</tr>
<tr>
<td>304</td>
<td>EG&amp;G dual four fold and</td>
</tr>
<tr>
<td>314</td>
<td>LeCroy dual four fold majority coinc.</td>
</tr>
<tr>
<td>315</td>
<td>LeCroy dual four fold majority coinc.</td>
</tr>
<tr>
<td>333</td>
<td>LeCroy dual amplifier</td>
</tr>
<tr>
<td>428</td>
<td>LeCroy quad linear fan in/fan out</td>
</tr>
<tr>
<td>429</td>
<td>LeCroy quad logic fan in/fan out</td>
</tr>
<tr>
<td>621L</td>
<td>LeCroy quad disc.</td>
</tr>
<tr>
<td>623</td>
<td>LeCroy octal disc.</td>
</tr>
<tr>
<td>710</td>
<td>Phillips octal disc.</td>
</tr>
<tr>
<td>711</td>
<td>Phillips 6 channel disc.</td>
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<tr>
<td>755</td>
<td>Phillips quad four fold coinc. with veto</td>
</tr>
<tr>
<td>794</td>
<td>Phillips quad gate gen.</td>
</tr>
<tr>
<td>GG</td>
<td>Joerger dual gate gen.</td>
</tr>
<tr>
<td>QP</td>
<td>Joerger quad disc.</td>
</tr>
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<td>Predet</td>
<td>AGS Predet 8 channel timing gen.</td>
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### CAMAC

<table>
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<th>Description</th>
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<td>EG&amp;G 24 channel latch</td>
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<td>2228</td>
<td>LeCroy 8 channel TDC</td>
</tr>
<tr>
<td>2249</td>
<td>LeCroy 12 channel ADC</td>
</tr>
<tr>
<td>2550</td>
<td>LeCroy 4 channel scaler</td>
</tr>
</tbody>
</table>
FIG. C.1: Fast trailer trigger logic I
FIG. C.2: Fast trailer trigger logic II
FIG. C.4: Fast trailer CAMAC
Appendix D

Run Statistics from the Si and W Targets

<table>
<thead>
<tr>
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<th>Silicon</th>
<th>Tungsten</th>
</tr>
</thead>
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<td>Thickness (cm)</td>
<td>0.122</td>
<td>0.01</td>
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<tr>
<td>Density (g/cm$^3$)</td>
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<td>19.3</td>
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<tr>
<td>Atomic mass (amu)</td>
<td>28.09</td>
<td>183.85</td>
</tr>
<tr>
<td>Total target events (K)</td>
<td>70.4</td>
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</tr>
<tr>
<td>Total beam particles (M)</td>
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<td>37.5</td>
</tr>
<tr>
<td>Cross section (barns)</td>
<td>0.54</td>
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</tr>
<tr>
<td>Date 1990</td>
<td>Run Number</td>
<td>Total Triggers</td>
</tr>
<tr>
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<td>------------</td>
<td>----------------</td>
</tr>
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<td>30 JUN</td>
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| Total     | 237269     | 20548208       |

**TABLE D.1:** Run statistics from the Si target
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<th>Beam Particles</th>
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</tbody>
</table>

**TABLE D.2:** Run statistics from the W target
Appendix E

Leading Edge Timing Compensation

This method relies on the fact that the rise time of the photomultiplier pulse is essentially independent of the maximum pulse height. The following diagram shows two typical pulses. It is clear that the larger pulse will fire the discriminator before the smaller one. For a pulse of amplitude $V_{\text{max}}$, a reasonable approximation of the pulse shape is

$$V(t) = e \cdot V_{\text{max}} \left(\frac{t}{t_r}\right)^2 \cdot e^{-t/t_f} \quad (E.1)$$

That is, a parabolic rise and exponential fall. This corresponds to a charge, $Q$, (into 50 $\Omega$) of

$$Q = \int_0^\infty \frac{V(t)}{50\Omega} \, dt = \frac{e \cdot V_{\text{max}} \cdot t_f^3}{25\Omega \cdot t_f^2} \quad (E.2)$$

Thus, the pulse shape parameterized in terms of charge is

$$V(t) = 25\Omega Q \frac{t^2}{t_f^2} e^{-t/t_f} \quad (E.3)$$
For short times \( t/t_f < 0.3 \),

\[
V(t) \approx \frac{(25\Omega Q)t^2}{t_f^2}
\]

The time, \( \Delta t \), of the threshold crossing \( V_t \) is given by

\[
\Delta t = \left( \frac{V_t \cdot t_f^3}{25\Omega Q} \right)^{1/2}
\]

\[
\Delta t = \frac{A}{Q^{1/2}} \quad \text{(E.4)}
\]

where \( A \) is a constant.
## Appendix F

### E810 Collaboration

*Experiment 810 - A Search for Quark Matter (QGP) and Other New Phenomena Utilizing Heavy Ion Collisions at the AGS*

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</tbody>
</table>
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