**PROGRESS REPORT
ON
THE STUDY OF THE PHASE STRUCTURE OF HADRONIC
MATTER BY SEARCHING FOR THE DECONFINED QUARK-
GLUON PHASE TRANSITION USING 2 TeV $\bar{P}$ -P COLLISIONS; AND
BY SEARCHING FOR CRITICAL PHENOMENA IN AN
EXCLUSIVE STUDY OF MULTIFRAGMENTATION USING 1 GeV/
NUCLEON HEAVY ION COLLISIONS**

Prepared by
Department of Physics
Purdue University
West Lafayette, Indiana 47907
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1. Fermilab Experiment E735

1.1 Introduction

E735 was proposed in 1983 as a dedicated search for the quark-gluon plasma (QGP) at the Fermilab Tevatron. The experiment was motivated by intriguing results from UA1 and UA5 as well as theoretical suggestions that one should be able to form states of energy density of about 10 times that of normal nuclear matter in proton-antiproton collisions at $\sqrt{s} = 1.8$ TeV. Lattice gauge calculations suggested that the phase transition from confined quarks and gluons to the deconfined state was first order, involving a large latent heat and a change from few degrees of freedom in the hadronic phase to many degrees of freedom in the QGP phase. Van Hove suggested that the correlation between average transverse momentum, $\langle p_t \rangle$, and the charged particle multiplicity per unit pseudorapidity, $dN_c/d\eta$, be used to search for evidence of the phase transition. In his picture, a rise in $\langle p_t \rangle$ vs. $dN_c/d\eta$, followed by a plateau, followed by a second rise, would signify the hadronic, mixed, and quark-gluon phases of nuclear matter, respectively. E735 was designed to carry out this program as a function of particle type at the C0 collision region of the Tevatron. Charged particles were measured in two ways. A scintillator hodoscope, consisting of 240 elements, gave coverage over 6.5 units of pseudorapidity. The hodoscope gave a fast first estimate of the event multiplicity and was used for event selection on-line. A central tracking chamber, CTC, was used to provide more precise tracking information off-line. It covered 3.2 units of pseudorapidity. The CTC was the responsibility of the Purdue High Energy Nuclear Physics group. The momentum of charged tracks was sampled by a small single arm spectrometer, consisting of tracking chambers and two time-of-flight arrays. Particle momenta

from about 0.15 GeV/c to 3.0 GeV/c, depending on particle type, were measured. Typically, a few tracks per event entered the spectrometer. A short 3 month test run was made during the spring of 1987. At this time, the CTC was still under construction. Final installation of the apparatus was made in May, 1988, followed by a year of running. Results from the main running period have been reported recently [1].

Although the main focus of the experiment was on the transverse momenta ($p_t \leq 1.5$ GeV/c) of centrally produced mass-identified particles ($\pi^+, \pi^-, K^+, K^-, \bar{p}$) as a function of charged particle multiplicity, some information has also been obtained on photons and neutral particles that decay into two or more charged particles. Figure 1 shows a plan view of the E735 detector as configured for the study of inclusive photon production. For this special study, the magnet was turned off, the TOF counters and magnet tracking chambers were removed, and an electromagnetic calorimeter was added. The calorimeter was made from 36 hexagonal NaI (TI) crystals, 6 inches in diameter and either 10 or 20 radiation lengths deep. The crystals were stacked in a rectangular array 61 cm high and 106 cm wide, located 2 meters from the beam line, and subtending the azimuthal interval $1.0^\circ \leq \phi \leq 18.1^\circ$ and the pseudorapidity interval $-0.16 \leq \eta \leq 0.37$. Data were taken during a two month period of our run and approximately 1.7 million events were obtained.

After calibration, the energy deposited into each crystal could be determined and the crystals were then clustered into showers. Using a Monte Carlo simulation of the detector response, it was found that 47% of the observed showers were due to photons or converted photons, and the remainder to charged or neutral hadrons. The photon spectrum also included additional background from these other sources, which was removed with the help of the simulation and various cuts on the data. A special store, in which some of the p or $\bar{p}$

Figure 1 Plan view of E735 apparatus for photon running. *PTH/PTH*, p and p trigger hodoscopes; *UBH/DBH*, upstream and downstream barrel hodoscopes; *ECH*, endcap hodoscopes, *CTC*, central tracking chamber; *ECC*, endcap chambers, *VC*, vertex chamber; *SM*, spectrometer magnet; *STC*, straw tube chambers; NaI, electromagnetic calorimeter.

bunches were missing, allowed us to estimate the contamination from beam-related background.

Figure 2 shows the inclusive photon differential cross section for $0.3 \leq p_t \leq 5 \text{ GeV/c}$. An enhanced yield of soft photons is expected if a (QGP) is formed. This arises due to the bremsstrahlung of quarks accelerating in the color field confining the plasma [2]. To deter-

Figure 2 The measured inclusive photon differential cross section from minimum bias pp collisions compared to the prediction of the empirical E735 simulation.

mine whether such an enhancement exists in the data, one must first remove the contribution due to the electromagnetic decay of hadrons, which should be the dominant component in the p_t range of interest. This has been estimated for decays of π^0 , η mesons, and sigma hyperons on the basis of our previous measurements of p_t spectra of various hadrons [1],

[3], and the use of isotopic spin symmetry considerations. The result is shown as the solid curve in Figure 2. The predicted spectrum is in good agreement with the data, permitting us to set an upper limit of 15% for any excess contribution of photons with p_t between 30 and 100 MeV/c.

During this past year we also analyzed $\sim 10^7$ events obtained in the standard running mode in order to determine the spectrum of ϕ^0 mesons and its dependence on charged particle multiplicity, N_c . Enhanced production of the ϕ^0 relative to non-strange mesons has been suggested as a possible signature of QGP formation [4]. The ϕ^0 decays to a charged kaon pair with a mean decay length of only about 10 fm. The procedure used to detect ϕ^0 mesons was to search for charged kaon pairs originating from a common vertex. The resultant K^+K^- mass distribution is shown in Figure 3. The background was estimated using like-signed kaon pairs. The background-subtracted ϕ^0 peak is shown in the inset and corresponds to 1144 ± 34 , where the error is statistical.

The ϕ^0 p_t spectrum is shown in Figure 4. The spectrum is exponential and an $\exp(-p_t/T)$ fit yields $T = 0.35 \pm 0.11$ GeV, which is comparable to the value from the $\bar{p}$ spectrum. A calculation based on the PYTHIA code[5] is in good agreement with the data.

Both the transverse momentum spectrum of the ϕ^0 and its production as a function of the charged particle multiplicity were examined. The data were divided into five multiplicity bins. Values of $\langle p_t \rangle$ were obtained from each of the spectra and the dependence of $\langle p_t \rangle$ on N_c is shown in Figure 5a. Within the limits of the error, $\langle p_t \rangle$ is independent of N_c , a result that is consistent with the slight increase with N_c predicted by PYTHIA. From our previously reported results for π^+ , π^- , K^+ , K^- , and $\bar{p}$, we can determine the ratio of ϕ^0 to charged

Figure 3 Invariant mass distribution of K^+K^- pairs. The dotted line shows the fit to the like sign kaon background. The inset shows the ϕ^0 peak after background subtraction.

particles N_c . The variation of this ratio with N_c is shown in Figure 5b. The ratio has a constant value of 0.10 ± 0.01 . The lack of an increase at large N_c , where one expects a contribution from the QGP, argues against QGP formation in these collisions.

Figure 4 Momentum distribution of ϕ^0 . The histogram is from the PYTHIA Monte Carlo.

Figure 5 (a) Average p_t and N_c correlations and histogram obtained from PYTHIA. (b) Ratio of the number of ϕ^0 mesons to the total number of charged tracks per event plotted for regions of charged multiplicity N_c .

2. Multifragmentation using the EOS-TPC

2.1 Introduction

In 1990 the Purdue High Energy Nuclear Physics group proposed an exclusive multifragmentation experiment at the Lawrence Berkeley Laboratory Bevalac. This experiment was grouped together with two other proposals to study flow, into an experimental program using the newly-built Equation Of State Time Projection Chamber (EOS-TPC). Test runs were conducted during the spring of 1992, and physics running commenced in the summer of 1992. The experimental program was completed in December of 1992, and the Bevalac was decommissioned in February 1993. Figure 6 shows the layout of the EOS apparatus.

The main features of the multifragmentation experiment are:

- the use of reverse kinematics, i.e., a heavy projectile incident on a light target. All of the interaction products have essentially the same (beam) velocity and are carried forward into the TPC and other ancillary detectors.
- the use of a new detector, the EOS-TPC. This device was designed and built by the Relativistic Nuclear Physics group at LBL. It features 15,000 pads on a plane, with each pad sampling the energy loss in the TPC volume at a 10 MHz rate. The TPC is thus capable of handling large charged particle multiplicities.
- the characterization of interactions on an event-by-event basis. This last point is explained in further detail below.

The Purdue High Energy Nuclear Physics group has a long history working in the field of nuclear fragmentation. Our previous inclusive studies have led us to suggest the

Experimental layout

Figure 6 EOS-TPC Plan View.

analogy between nuclear fragmentation and a liquid-gas phase transition occurring in a van der Waals gas [6]. Recently, Campi has analyzed 400 exclusive gold-emulsion events and concluded that nuclear fragmentation has the characteristics of a critical phenomenon [7].

The Bevalac experiment will allow us to extract the critical exponents describing the phase transition, derived from moments of the charged species distribution. Using the EOS-TPC and a Multiple Sampling Ionization Chamber (MUSIC), the momentum and charge of almost every charged particle (including projectile fragments) will be determined. Events can be characterized as subcritical, critical, or supercritical, according to charged multiplicity and the size of the projectile spectator residue. We employed a Time-of-Flight (TOF) Wall to provide "seamless" coverage from the charge capability of the TPC, approximately charge 1 to 7, to that of MUSIC, charge 6 and higher. In addition, a detector capable of determining neutron spectra (MUFFINS) has been added.

2.2 1992 Running and Analysis

During the 1992 running period at the Bevalac, the entire EOS-TPC experimental program was successfully executed. Both symmetric and asymmetric nuclear collisions were studied at numerous incident energies. In the flow physics program, an effort was made to cover ranges in both the colliding system size and energy of previously existing

For the nuclear fragmentation program, the emphasis was on measuring fragments of projectiles of widely differing size at 1 GeV/nucleon. The quantity of data written to for each of the physics runs is shown below in Figure 7. Analysis of these data is presently underway. In particular, physics results are emerging from the flow analysis. Preliminary results indicate for the Au + Au system that flow continues to increase at Bevalac energies.

Multifragmentation and particle correlations will be the focus of the Purdue group's effort during the analysis phase of the experiment. To this end, we have begun the major

EOS Events with INT Trigger

Figure 7 Events written to tape.

tasks of understanding each individual detector subsystem and matching tracks between these subsystems. Details of this will be briefly discussed below.

2.3 Analysis of the MUSIC detector

Unlike the flow analysis, which can be done (in preliminary stages) on low Z particles identified by the TPC, the multifragmentation analysis is more dependent on detection of the high Z particles. The moment and sphericity analyses must be performed on the complete, reconstructed events, requiring the detection of large fragments by MUSIC and the Time-of-Flight Wall.

MUSIC, like the TPC, is a gas filled detector. MUSIC is made of three separate field cages, each 1 m by 60 cm by 50 cm, filled with P-10 gas. Two of the field cages detect the horizontal position of the particles; the other detects the vertical position.

The initial pass through the EOS data is used to determine quantities that may vary from run to run such as the drift velocity. For MUSIC, the drift velocity is calculated using the maximum drift distance and the maximum drift time. Baseline runs taken during the running period are used to interpolate for the baseline values for each data run. A check of the charge assignment which depends on the absolute gain calibration is made using the beam particles.

This initial pass is in progress now. In the second pass through the data, the spatial position of hits in the detector will be determined using the drift velocity found in the first pass. In a third pass, tracks will be constructed from the hits. The output of the third pass will be the data summary tapes. The data on these tapes will be used for matching tracks between detectors.

The information from MUSIC's three field cages will be correlated to create the tracks detected by MUSIC in each event. Then particle tracks in MUSIC will be extended to the TOF Wall and matched in both charge and space. The TOF and TPC will also be matched. Particles seen in two detectors provide a relative calibration of the two. All valid tracks (those which pass vertex and quality cuts) from all detectors will then be combined and the information from the matched tracks used to reconstruct the entire event.

2.4 Analysis of the Time-Of-Flight Wall

The Time-Of-Flight (or TOF) Wall consists of 98 slats of scintillating plastic read out by a photomultiplier tube at each end. Each slat has an effective length of 1 m and is 2 cm wide and 0.7 cm thick. The slats are arranged in two walls with 49 slats in each wall. The centers of the slats in each wall are offset to insure complete coverage of approximately one square meter.

The TOFTOF Wall is capable of complete charge coverage, from protons to the charge of the beam. In the EOS experiments, the TPC provides detailed information about low charge particles, $1 \leq Z < 6$. The MUSIC II detector covers the heavier charged fragments, $8 < Z \leq Z_{beam}$. The TOFTOF Wall will be used as a redundant detector system for both the TPC and MUSIC, but will also provide coverage of the charges missed by the TPC and MUSIC, $6 \leq Z \leq 8$. The TOF Wall's coverage of this mid-charge region allows complete charge coverage for each event.

Calibrations for the TOF Wall charge determination are based on data taken from sweeps of beam particles across the Wall. For each sweep and each slat the geometric mean

of ADC's, on each end of the slats, are calculated. The position of this peak is used to calibrate the slat and later determine the charge of particles passing through that slat.

Beam sweep information is also used for timing calibrations. The beams were swept through the middle of each slat and thus provide a timing offset to account for cable delays. Calibrations for runs in the fall of 1992 are complete, and calibrations for the summer of 1992 are underway.

At this point the timing resolution for a single slat is 260 ps. However, after various amplitude walk corrections have been implemented the timing resolution is expected to improve to 180 ps. The charge resolution for heavy fragments, $Z > 10$, is approximately a quarter of a unit of charge. More information concerning the resolution of heavy fragments will be available when tracks can be matched between MUSIC and the TOF Wall. Algorithms for matching tracks in MUSIC and the TOF Wall are currently under development.

Track matching between the TPC and the TOF Wall will provide information concerning low charged particles, $Z < 6$. Matching between the TPC and the TOF Wall is at a preliminary testing stage. The tracking of low gain TPC runs (runs with only beam particles) is in progress.

2.5 GEANT Simulations

The GEANT simulation of the EOS experiments has been integrated into the EOS analysis software package. This step was taken to facilitate a comprehensive event reconstruction efficiency study. In this study, which focuses on the TPC, the analysis software is to be tested by simulating the data at the pad response level within GEANT, and using the results as input to the analysis chain.

The simulation of an event involves several steps. First, a statistical event generator employing a physical model of the collision dynamics is used to produce the particles. These are allowed to stream through a simulation of the TPC detector, provided by GEANT. A third stage of the simulation reproduces the TPC response to the passage of the particles. The end result of this chain of codes is simulated event data that matches the real event data (as output by the data acquisition) as closely as possible. The development of these codes is nearing completion. Test runs of the software for 1 GeV/Au + C events are being conducted.

The efficiency of the data reduction algorithms for reconstructing quantities such as the multiplicity and the momentum, will be studied as a function of multiplicity. The multiplicity reconstruction efficiency is especially important for the critical exponent analysis, as the distance from the critical point is determined by the multiplicity. Additionally, if the distance from criticality is determined from the transverse energy, the momentum reconstruction efficiency becomes crucial. Any event shape analysis also depends on a knowledge of the quality of the momentum reconstruction.

A study will be made of the combined impact of a partial event acceptance plus detector inefficiencies on the physics analysis. In particular, comparisons will be made between the physics results calculated from complete simulated data sets, and results from simulated data sets subjected to the analysis chain.

3. STAR R&D

3.1 Introduction

The Solenoid Tracker at RHIC (STAR) collaboration will use a central Time-Projection Chamber (TPC) to measure the charged particles produced in relativistic heavy ion collisions. This TPC will have an inner radius of 0.5 m, an outer radius of 2 m and a longitudinal length of 4.2 m (see Figure 8). The pseudorapidity coverage (full track length inside the TPC) will be $-1 < \eta < 1$. The TPC will measure both track position and energy deposited, dE/dx .

Figure 8 The STAR Detector.

In the TPC, ionization electrons produced by traversing particles will drift towards both ends with a maximum drift length of about 2.1 m. The readout end caps will be divided into sectors, 48 in total. Because of the high multiplicity of central Au + Au collisions at RHIC, ($dN/d\eta \approx 2000$ including secondary particles) two sizes of pads are planned for the readout sectors. These pads will measure 2.85 mm x 11.5 mm for the inner sectors and 6.2 mm x 19.5 mm for the outer sectors. While the large-size pads have been used in many TPC experiments, the small-size have not.

The small pads used in the inner sectors will increase the two-track resolution. This is crucial in a high-multiplicity environment in order to obtain hit positions and dE/dx measurements. In addition, the gap between anode and pad plane is reduced from 4 mm for the outer sectors to 2 mm for the inner ones. This new geometry needs to be extensively tested for gain variations and pad response function measurements.

As part of the Purdue group's continuing participation in the STAR collaboration, we have mounted a strong effort this year in the R&D for the TPC. This has included establishing a testing lab at Purdue where extensive tests were performed on a small pad plane prototype chamber. Our goal was to establish the feasibility of the small pad readout and to measure the characteristics of the prototype pad chamber including gain, pad response function and intrinsic resolution.

As R&D is phased out and construction begins, the Purdue group is committed to providing TPC sector production testing and quality control. Towards this end, a testing station based on a Macintosh Quadra 800 is being developed now, with the first sector anticipated to arrive in August, 1993 for testing. Future testing will shift to LBL under Purdue supervision.

We report here on the test results obtained from the small prototype chamber from January to June 1993.

3.2 Hardware Setup

The tests were done on a small pad prototype chamber constructed at LBL. The specific goals of the tests were:

- To measure the gain variations across the chamber for this geometry.
- To study in detail the Pad Response Function (*PRF*) for the small pads that will be used in the final TPC.
- To investigate the *PRF* for curved pad rows.
- To study the ultimate precision for locating tracks in the chamber.

A top view of the chamber is shown in Figure 9 where the 4 curved pad rows can be seen. Figure 10 shows a schematic of the chamber showing the four planes - drift plane/gas window, ground grid, anode/field, and pad plane. The chamber had a removable gas window/drift plane combination so that separate windows could be used for the source and laser. A three axis positioning system above the drift plane moved the laser or source in known increments.

The data acquisition system is shown in Figure 11. The system is a copy of the LBL-EOS acquisition system and uses the LBL-EOS stick electronics to read out the pads. The SUN Sparc 10 is used to control data taking and to display events. Auxiliary on-line programs also run on the SUN and provide data summations etc. To normalize the data we also read out the anode wires and displayed the results on a digital oscilloscope or on a multi-channel analyzer.

Mini-Pad Prototype: Cover Removed

Top View

All Dimensions In Inches

Figure 9 Engineering Drawing of Prototype Pad Plane.

Drift Plane: p For Fe 55 Measurements - Mylar window with conductive TiO on inside

p For Laser - Quartz Window with Al coating on inside -250 V

Field Wires: Ground Potential $\phi = 125 \mu\text{m}$, Be-Cu

Anode Wires: +HV, $\phi = 20 \mu\text{m}$, gold-plated tungsten

Pad Plane: 2.85 X 11.5 mm Pad
3.35 mm pitch
Curved Pad Rows

Gas: 90% Ar - 10% Methane

Figure 10 Perspective Drawing of Prototype Pad Plane.

Experimental Set-Up

Figure 11 Data Acquisition Setup for Prototype Tests.

3.3 Gain Measurements

One unique feature of the small pad readout is the reduced gap of 2 mm between the anode and the pad plane, resulting in an asymmetric electrostatic potential around the anode wires. (Figure 10) Since gas gain is strongly dependent on geometrical considerations it is very important to maintain strict tolerances for such things as wire placement, wire tension, inter-plane distances and planarity. Thus we have spent some time investigating the gain response of this small prototype chamber and, in the future, gain measurements will constitute a large portion of the pass/fail tests for the final sectors.

We measure gain by using an ^{55}Fe source which deposits a known energy fully in the gas volume, and thus gives an easily recognizable peak in pulse height. Figure 12 superimposes the relative gain for two anode wires each at the chamber edge and center. By cali-

Figure 12 Relative Gain for 4 Wires Using an Fe Source.

brating the electronics with a known amount of charge, we can get an absolute gas gain, shown in Figure 13 for the same wires.

Proper functioning of the final STAR TPC will depend directly on having a uniform gas gain throughout the chamber volume. Figure 14 shows the relative gain for each anode wire at both ends of the wires. The gain variation is $\delta g/g < 1.5\%$. Figure 15 shows the gain variation along the wire number 27 (near center). Again the gain variation is less than 1.5%. Thus, we have achieved a gain uniformity better than 1.5% over most of the active volume of the pad chamber.

Systematic errors in wire placement could lead to systematic shifts in gain. To look for such effects, the (x, z) coordinate of each wire (at each end of the chamber) were measured by microscope at LBL. These distributions are shown in Figure 16 for z and Figure 17 for x , where we plot the deviation from the theoretical x wire pitch (4.0 mm). In summary, the position resolution in the direction perpendicular to the anode plane is better than 15 microns, and is better than 100 microns in a plane parallel to the anode wires. We do not observe a correlation between the gain variation and the geometrical asymmetry.

3.4 Pad Response Function Measurement

The pad response function (PRF) is defined as the amplitude of the pad signal as a function of the distance of the avalanche from the center of the pad. It depends on the pad geometry (size and orientation with respect to wire), as well as on the induced charge distribution from the avalanche (determined by the gap and capacitive coupling between anode and pad planes). The laser setup was used in the PRF measurement. The nitrogen laser (VSL-337 from Laser Science, Inc.), triggered by an external pulse, was focused onto an

Figure 13 Absolute Gain For 4 Locations.

Figure 14 Relative gain measured at both ends for 33 anode wires.

Al-coated quartz window. Due to the unevenness of the window surface and the space charge from positive ions leaking into the drift region, there are large variations, up to 30-

Figure 15 Relative gain measured along one anode wire.

50%, in the amplitude of the anode signals, and consequently in the pad signals. To eliminate this effect the anode signal amplitude is read out by a digital scope and used to normalize the pad pulse height.

Figure 18 shows the pad response function parallel to the anode wires for pad channels 63, 64 and 65. These correspond to the fourth, fifth and sixth pad from the readout end on the middle short pad row, where there is no significant curvature with respect to anode wires. The lines are Gaussian fits to the measurements with a sigma of about 2.2 mm. The pad response function along the anode wires is generally considered a Gaussian distribution, to a good approximation. Theoretical calculations by Gatti et al.[8] and subsequent approximate parametrization by Mathieson [9] indicate a slight deviation from Gaussian. Early measurements by Fancher and Schaffer [10] have shown a deviation at the level of a few percent of the PRF amplitude. Figure 19 shows the residual from subtracting a Gaussian fit from the data. The dashed lines are the PRF data scaled by 3.4%. Note that both mea-

Figure 16 Z positions of the anode wires.

measurements with wide pads (7.5 mm width) by Fancher et al. [10] and by Sobel et al. [11] indicated a dip in the residual distribution at the middle of the pad. However, our measurement with narrow pads (2.85 mm width) indicates a small peak in the residual at the center of the pad.

Figure 17 Deviation in X position of anode wires from pitch of 4 mm.

The pad response function perpendicular to the anode wire is expected to be several steps across because the avalanche position is localized on each anode wire with a constant pitch of 4 mm. However, due to a finite laser size and diffusion in the gas the edge of each step would be smoothed. Figure 20 shows the PRF perpendicular to the anode wires for pads in the straight section of the pad row (near the readout end). The slight asymmetry of both sides of the PRF is due to small offset between wire pitch (4 mm) and pad length (11.5

Figure 18 Pad response function parallel to the anode wires at the straight section of the second row.

mm). The shape of the PRF for two neighboring pads is very similar to that of the central

Figure 19 Residual of pad response function subtracted by Gaussian fit.

pad; a small difference at the edges may be due to the fact that the PRF is not completely decoupled in X (perpendicular to wire) and in Y (parallel to wire) directions.

Figure 20 Pad response function perpendicular to the anode wires for pads in the straight section of the pad row.

The PRF for straight pad rows versus curved pad rows has also been studied. This is important for high momentum particles which have little bending inside the TPC volume. For straight pad rows these particles from the interaction vertex have an incident angle up to 15 degrees with respect to the pad row. Figure 21 shows the PRF for pads from a straight section of the row, when the incident angles between the laser scan and the direction perpendicular to wire are 8 and 15 degrees respectively. There is a strong asymmetry in the PRF between the two neighboring pads. Thus for a traversing particle which produces avalanches on all anode wires along the path, the Landau fluctuation in the ionization could significantly deteriorate the accuracy of position measurement.

For circular pad rows, however, the PRFs for high momentum particles from two neighboring pads are approximately symmetrical. Figure 22 shows the PRF measurement

Figure 21 Pad response function with scan angles of 8 and 15 degrees for pads in the straight section of pad row.

when the laser scans radially. Thus in this geometry the effect of the Landau fluctuation in the ionization could be reduced.

Figure 22 Pad response function with radial scan for pads in the circular section of the pad row.

Concerns were raised for the circular pad rows that the coupling between anode and pad will be strongly position dependent, which could compromise the dE/dx measurement.

Simulations showed that the improvement due to circular pad rows in momentum resolution for high momentum particles is marginal. Therefore, there is little gain in the physics capability of the STAR TPC by using circular pad rows. The decision will largely be based on convenience in sector manufacture.

3.5 Resolution Measurement

The geometrical choices of pad size and gap width are determined by the position resolution and two track resolution. These resolutions are also coupled to the signal-to-noise ratio of the pad readout electronics. We studied the intrinsic position resolution of the small pad chamber for signal-to-noise ratios ranging from 200 to 400. The laser scan is performed parallel to the anode wire, and the position of the laser is calculated using signals from three or two pads. The variation of the position reflects the intrinsic resolution associated with the pad geometry. The resolution due to systematic errors is studied by comparing the calculated position versus scan position over many pads.

The avalanche position can be calculated from three or two pads. For the three pads case, the measured signal amplitudes are considered parts of the Gaussian pad response function (PRF). The sigma of the PRF is $\sigma = g / (\log(h_2^2/h_1/h_3))^{1/2}$, where h_1 , h_2 and h_3 are signals from pad number 1, 2 and 3, and g is the pad pitch (3.35mm). The position of the avalanche can be deduced from the Gaussian PRF: $x = \sigma^2 \log(h_3/h_1) / (2g) + g/2$. For the two pad case, the Gaussian PRF is not defined by the two pads. We must assume the σ of the Gaussian PRF (2.15 mm). Then the position can be calculated as $x = \sigma^2 \log(h_2/h_1) / g + g$.

Figure 23 shows the measured width σ in mm as a function of laser position. The σ reaches a minimum in the middle of the pad and increases by 150 microns at the edge of

the pad. To understand this modulation we recall that the pad response function we have

Figure 23 The width, σ , of the pad response function as a function of laser position measured from three pads.

measured is not exactly Gaussian. There is a deviation from the Gaussian up to 3.4%. Using a function that was suggested to describe the induced charge distribution on the pad plane

[10], we obtained a better fit to the measured PRF. The calculated σ from this fit is shown in Figure 24 as a function of the avalanche position. We reproduced the essential feature and magnitude in the variation of σ .

Figure 24 Expected width as a function of the avalanche position from the pad response function measurement as shown in Figure 18.

Figure 25 shows the calculated position (top panel), the position resolution (σ , not to be confused with that for the width of PRF) (middle panel) and the position deviation (bottom panel) as a function of the laser position for the three pad fits. The intrinsic position resolution with a signal-to-noise ratio of 200-400 for this pad geometry is about 40 microns. The position accuracy including systematic errors is about 100 microns. The modulation in the position deviation is due to the non-gaussian nature of the PRF.

The effect of this non-gaussian nature of the PRF is greatly amplified in the two pad fits. Figure 26 shows the calculated position, the position resolution and the position deviation as a function of the laser position using two pad fit. The width of the PRF, σ , has been fixed at 2.15 mm. Note there is a discontinuous jump in the position calculation at the center of the pad, where the pad numbers used for the two pad fit change. This can be attributed to the non-Gaussian nature of the PRF. Figure 27 shows the expected deviation for the two pad fit as a function of the laser position. Both the shape and the magnitude are consistent with our observation. The gain variation in the electronics of the pad readout system could contribute to additional smearing in the measured data.

The resolution measurements for the curved sections of the pad rows yielded similar results as shown in Figure 24-Figure 27.

3.6 Two-track Resolution Measurement

We studied the intrinsic two-track resolution of the pad chamber using several laser beams. A splitter box from Laser Science, Inc. with one fiber for input laser beam and seven fibers for output beams was used to generate two signals. To reach the minimum distance

Figure 25 Calculated position, position resolution, and position deviation as a function of the laser position for three pad fits.

of separation, we removed the focus lens. The laser spots should still be in the range of several hundred microns since the diameter of the fiber is only 200 microns.

Given a pad geometry, the two-track resolution depends on the relative signal strength, signal-to-noise ratio and the algorithm to calculate the hit positions. For the three

Figure 26 Calculated position, position resolution, and position deviation as a function of the laser position for two pad fits.

pad fit there is no ambiguity in selecting which three pads to use. However, for two pad fit we have to decide which two pads to use for the fit since one avalanche normally induces signals on three pads. Current analysis was based on visual examination of the pulse amplitude from all pads: normally two pads with the largest signals were used in fit, but when

Figure 27 Expected position deviation as a function of the laser position for two pad fits.

two lasers were close to each other two pads away from the other laser were used. This procedure can be optimized, but the results presented here remain essentially the same.

Figure 28 shows the lego profile of the pad amplitude as a function of separation between two signals. At the starting point of about 13 mm apart, signals from two lasers are clearly separated. However, as the two lasers approach a distance of 6 mm apart there is

only one broad peak in the pad signals. This scan was performed along the anode wire in the straight section of the pad row. The signal of the fixed laser is about 70% of the moving laser.

Figure 28 Lego profile of the pad amplitude as a function of laser separation. Note that the intensities of the two lasers are comparable.

Figure 29 shows the calculated positions for the fixed laser. The jump in the two pad fits is due to the non-Gaussian nature of the pad response function, which has been discussed in the previous section. This jump also indicates the position where different sets of two pads were used in the fitting. The calculated positions from two pads are within 300 microns to the actual position for laser separation down to 6 mm. This constant offset could probably be corrected for by using a more accurate description of the pad response function. However, for three pad fits the position deviation increases as two lasers approaching each other. The deviation reaches more than 1 mm for laser separation less than 6 mm. Figure 30 and Figure 31 show the calculated position and deviation as a function of laser separation for the moving laser. In this case, the modulations in the position accuracy discussed in the previous section are also noticeable.

This measurement indicates that for the small pad geometry we can measure track positions for two tracks as close as 6 mm. However, the two-track resolution for dE/dx measurement (three pad fits) is close to 10 mm. This is consistent with our expectations from initial design considerations for the small pad geometry.

3.7 Conclusions

We have measured the characteristics of the small pad geometry. The pad response function has a width, σ , of about 2.15 mm, suitable for accurate position measurements. We have achieved an intrinsic position resolution of 40 microns and a systematic position resolution of about 100 microns. The two-track resolution for position measurements is about 6 mm and that for dE/dx measurements is about 10 mm when measured with lasers of equal intensities. The two-track resolution for position measurement approaches 10 mm when

Figure 29 Position calculated from two and three pad fits for the fixed laser.

two lasers with greatly different intensities were used. The successful operation of this pad chamber proves the feasibility of the small pad design for inner sectors of the STAR TPC.

Figure 30 Position calculated from two and three pad fits for the moving laser.

Figure 31 Position deviation as a function of the laser separation for the moving laser.

4. Silicon Avalanche Diodes as Direct Time-of-Flight Detectors

4.1 Introduction

Since 1991, the Purdue High Energy Nuclear Group has worked on a research and development project to investigate silicon avalanche diodes (AVDs) as time of flight (TOF) detectors for nuclear and particle physics applications. The principle is *not* to use the AVD as a photodetector coupled to a scintillator, but rather to *detect the ionization of charged particles directly in the silicon*. The major result obtained is the demonstration of feasibility: AVDs have been shown to be directly sensitive to minimum ionizing particles with a useful signal-to-noise ratio. A time resolution of $\sigma = 65$ ps has been obtained. This time resolution is comparable to the best obtained with the conventional alternative, a plastic scintillator and photomultiplier tube (PMT), and further optimization of the AVD results appears possible.

Two types of AVDs have been tested to date. The first of these was purchased from EG&G Optoelectronics Division, Montreal, Canada. The sensitive area of these diodes is $5 \times 5 \text{ mm}^2$, and they have an effective thickness of $140 \mu\text{m}$. The modules include a preamplifier. The diodes have an operating voltage of ~ 400 V and an internal avalanche gain of ~ 50 . A second generation of AVDs was purchased (more recently) from API (Advanced Photonix Inc., Camarillo, California). The sensitive area is circular, 98 mm in diameter, with an effective thickness of $250 \mu\text{m}$. Only the center 5 mm diameter was exposed to the β rays. These modules also include a preamplifier. Their operating voltage is ~ 2200 V and the internal gain is ~ 200 .

Basic measurements were made using facilities available at Purdue. For both types of diodes, the time resolution was measured by exposing two diodes in coincidence to minimum ionizing (β^-) particles. The width of the histogram of the time differences between the two diode signals is the time resolution. The β^- went through the silicon of each of the diodes, and stopped in a plastic scintillator coupled to a PMT. Only high energy β^- that went straight through two collimators and the two diodes were recorded: a pulse height cut on the scintillator signal selected the high energy tail of the β^- spectrum, and a triple coincidence was required among the two diodes and the scintillator to trigger an event. See Figure 32.

The signal is created in the diodes by the ionization energy loss (dE/dx) of the β^- , which creates electron-hole pairs in the silicon. The electrons drift in a strong electric field to the diode junction, where they multiply in an avalanche region. In the EG&G diodes, which are of the reach-through design, the best ratio of the multiplicity-weighted electron-hole multiplication to the multiplicity-weighted electron multiplication is typically $k = 0.02$, implying a maximum useful current gain of 50. The second generation API diodes are of the deep diffusion, beveled edge type, and have a value of $k = 0.001$. The maximum useful gain expected is 1000. This internal gain is essential because it boosts the signal prior to the (inevitable) addition of noise in subsequent amplification steps. Each diode channel of the test setup used an additional fast, low noise amplifier, and then split the signal to a charge sensitive ADC and a leading-edge discriminator (LED). Start and stop from the LEDs were fed into a Time to Pulse Height Converter (TPHC), which then fed a shaped pulse into a peak-sensing ADC.

Figure 32 AVD Test Setup

4.2 Expected AVD Signals

A simple and accurate estimate of the expected AVD signal characteristics can be made. The most probable energy loss of a minimum ionizing particle in 140 μm of Si is about 34 keV, so each β^- produces about 9,500 electron-hole pairs. After the subsequent amplifications, the expected output is 5.7×10^8 electrons. The signal rise and fall times should be $t_{rise} = 2.5 \text{ ns}$, $t_{fall} = 5 \text{ ns}$, and the FWHM should be $t_{fwhm} = 5 \text{ ns}$. The peak current is expected to be $\sim 18 \text{ mA}$ (5.7×10^8 electrons in 5 ns), corresponding to an expected $\sim 900 \text{ mV}$ peak output signal (into a 50Ω load).

Fluctuations in the signal are expected from the Vavilov distribution of dE/dx , diode avalanche gain nonuniformity, and preamplifier noise. The dominating source of signal fluctuations is the preamplifier noise; the expected noise is 20 mV RMS. Since the noise fluctuates positive and negative, this gives an expected signal-to-noise ratio of $900 \text{ mV} / (2 \times 20 \text{ mV}) \cong 23$. The observed preamplifier noise is fully consistent with these expectations. For a leading edge discriminator, the expected time resolution can be estimated directly from the slope of the pulse at the discriminator threshold and the RMS noise. The time that a linearly rising signal crosses a fixed threshold will vary simply as

$$\sigma_{time} = \frac{\sigma_{noise}}{\left(\frac{dV}{dt}\right)}$$

Thus, the optimal trigger level for the leading edge discriminator is at the level where the pulse slope is a maximum.

4.3 Experimental Results - EGG Diodes

The experimental pulse shape of the β^- signal in the EG&G AVD rises from 10% to 90% in ~ 2.5 ns as expected, and the falltime is ~ 9 ns. The FWHM is ~ 7.5 ns. The pulse is asymmetric about the peak, and there is no plateau at the top. The maximum pulse height is ~ 1 V, as predicted. The ADC spectrum of the β^- pulses peaks in channel ~ 500 . The FWHM of the distribution is $\sim 40\%$.

Multiplication has been measured versus V_{bias} . These measurements are comparable to gains obtained by optical measurements performed by EG&G using laser input. See Figure 33. However, at the highest bias voltages, the optically measured gains are at most about 25% higher than the gains measured using the β^- source. This deviation may be due to gain variations across the diode. The optical measurements are made at the center of the diode, whereas the β^- gain measurements average over the entire diode. Lower gains at the edges would lower the average gain and could lead to the observed difference.

The time spectrum of two EG&G AVDs with β^- pulses in coincidence was taken with LEDs and a TPHC-ADC system with 5.54 ps/channel and ~ 9 ps intrinsic time dispersion. The data were corrected for amplitude walk, and the resulting histogram of corrected time measurements was fitted with a Gaussian. Since the time measurements are made with two diodes, the variance of this distribution is the sum of the variances of the individual diodes. Individual time dispersions were found by timing the diodes against each other in all combinations of pairs. Figure 34 shows a histogram taken with two diodes which were found to have approximately equal time dispersions, so they contribute equally to the variance. Thus, for the distribution shown, we have

Figure 33 Gain versus bias voltage.

$$\sigma_{D1} = \sigma_{D2} = \frac{91.8ps}{\sqrt{2}} = 65ps$$

for each of these individual diodes. The range of σ 's is 65 - 85 ps for the set of four diodes tested.

Figure 34 Corrected time-of-flight. Note that the standard deviation is for two diodes.

4.4 Experimental Results - API Diodes

The pulse shape in the API AVD rises from 10% to 90% in ~ 2 ns, with a fall time of ~ 40 ns. The pulse is asymmetric, with a typical pulse height of 500 mV and FWHM of ~ 20 ns. There is a small dip near the peak, presumably due to a slow current component. This slow component comes from a layer near the surface which is not fully depleted. The drift velocity here is lower than the saturation drift velocity, due to the lower electric field.

Time dispersion measurements have also been made for the API diodes. The techniques outlined above were used. Better time resolution is expected for these diodes because of their 2ns risetime and order-of-magnitude higher gain. In initial measurements, $\sigma \sim 90$ ps was obtained. However, efforts are presently underway to improve this value. The significant slow component of the pulse contributes to the integrated pulse, but does not contribute strongly to the fast timing signal. Thus, the amplitude measured in the charge-sensing ADCs is not adequate for proper amplitude walk correction. A clipped and stretched signal will be used in the future for such walk corrections. The time dispersion is comparable to that of the EG&G diodes.

In both types of diodes, the time resolution does not vary strongly as a function of temperature or voltage.

AVDs have delivered their promised time resolution in these experiments. The observed signals are generally consistent with expectations, and more refined calculations and comparisons are underway. Further improvement of an AVD system for timing applications should be possible. See attached preprint.

5. Soft Photons at the AGS - E855

Experiment E855 ran at the AGS in 1990. Groups from ORNL (including M. Tinnell, now at Purdue), BNL, CERN, and Vanderbilt University collaborated. The experiment used two 19 crystal arrays of BaF₂ scintillator to detect photons, and a 24 element plastic scintillator hodoscope to measure charged particle multiplicity. Collisions of p+Be and p+W at 10 and 18 GeV were recorded, to search for the possible production of anomalous photons in the central rapidity region with transverse momentum between 5 and 50 MeV/c. The major known sources of photons in this range are from π^0 decays, and hadronic bremsstrahlung from the charged particles produced in the collision. Because of the kinematics of π^0 production and decay, and the $1/\omega$ photon energy dependence of bremsstrahlung, the combination of these known sources has a minimum in this range. This presents a window to look for photons from additional sources, without being swamped by known backgrounds.

Several experiments at higher energy have reported photon abundances in this kinematic region from 2 to 10 times that expected from the known backgrounds. E855 is a sister experiment to one run at the SPS at CERN using the same BaF₂ array. In 1992, the SPS experiment released its findings, correcting an earlier (preliminary) claim of photon levels 5 to 10 times higher than expected. The new result is a limit on any excess of <50%, and no claim of any excess at all.

Analysis of the E855 results from the AGS will be completed by the end of 1993. The data for final analysis were selected with several cut criteria to insure integrity. A neutral event was required by plastic scintillator veto detectors in front of each BaF₂ array. The crystal with maximum energy was required to be in the central area of the detector to insure

good lateral energy containment and position resolution. The fast scintillation of BaF₂ was utilized to time the arrival of neutral energy with a resolution of $\sigma=400$ ps. This allowed rejection of most neutrons and secondary photons. E855 also employed a hadron calorimeter behind one BaF₂ array to veto fast, high energy neutrons.

Monte Carlo studies have been used to give factors for photon trigger efficiency, energy resolution and leakage, and geometrical acceptance. Corrections for charged particle overlap, more than one photon hit, and photon losses in the cuts have also been made. Empty target subtraction (to reject beam-related backgrounds) and finite target-thickness extrapolation (to correct for secondary interactions in the target) have also been done.

The major source of photons is π^0 decay. In order to account for these photons, the π^0 rapidity distribution was assumed to be Gaussian, and the p_T distribution was assumed to be exponential in $m_T = \sqrt{p_T^2 + m^2}$. This distribution function is consistent with the phenomenological distribution of charged pions obtained in other (spectrometer) experiments. A five parameter, non-linear fit was made of these functions to the experimental photon rapidity and p_T distributions, using π^0 decay kinematics, and the E855 photon spectra obtained at several rapidities. All photons in the p_T range 50 to 400 MeV/c were assumed to come from π^0 decay. The derived photon distribution was then subtracted from the observed distribution to remove the π^0 background. The data for 18 GeV p+Be and p+W have been compared with charged pion spectra from AGS E802 at 14.6 GeV, and with FRITIOF and ARC Monte Carlo event generators. The E855 π^0 rapidity distribution agrees reasonably well with the E802 $\pi^{+/-}$ rapidity distributions.

A theoretical analysis of the expected bremsstrahlung yield from all incoming and outgoing charged particles has been made, using two different calculations. Both agree

within $\sim 45\%$ for both p+Be and p+W over the entire p_T range. These distributions were also subtracted from the data to obtain the final p_T spectra attributable to unknown sources.

The final results show no significant excess of soft photons at $y_{cm} = 0$ for 18 GeV p+Be. The data over the p_T range 8 to 1000 MeV/c are quite consistent with only photons from π^0 decays and charged particle bremsstrahlung. See Figure 35.

Graduate student Robert Clark of Vanderbilt University, under joint supervision by C. Woody of BNL, and M. Tincknell of Purdue, will finish his Ph.D. thesis on this in early 1994. A Physical Review Letter will also be submitted by the end of 1993. A further paper on photons from nuclear de-excitation in p+W collisions is also anticipated. This will complete experiment E855.

Figure 35 Photon transverse momentum spectrum for Be at $y_{cm} = 0$.

6. Publications

These cover the period September 1992 - June 1993.

- [1] **Sub 60 ps Timing Resolution Using Large Area Silicon Avalanche Diodes**, presented at the IEEE Nuclear Science Symposium, Orlando FL, October 25-31, 1992, to be published in the Proceedings.
- [2] **A Study of Source Size in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV Using Pion Interferometry**, T. Alexopoulos, C. Allen, E. W. Anderson, H. Areti, V. Balamura, S. Banerjee, P. D. Beery, P. Bhat, J. M. Bishop, N. N. Biswas, A. Bujak, D. D. Carmony, T. Carter, P. Cole, Y. Choi, R. De Bonte, V. DeCarlo, A. Erwin, C. Findeisen, A. T. Goshaw, L. J. Gutay, A. S. Hirsch, C. Hojvat, J. R. Jennings, V. P. Kenney, C. S. Lindsey, C. Loomis, J. LoSecco, T. McMahon, A. P. McManus, N. Morgan, K. Nelson, S. H. Oh, J. Piekarz, N. T. Porile, D. Reeves, A. Rimai, W. R. Robertson, R. P. Scharenberg, R. Stampke, B. C. Stringfellow, M. Thompson, F. Turkot, W. D. Walker, C. H. Wang, J. Warchol, D. K. Wesson, and H. Zuong, (submitted to Phys. Rev. D.)
- [3] **Mass Identified Particle Production in Proton-Antiproton Collisions at $\sqrt{s} = 300, 540, 1000$, and 1800 GeV**, T. Alexopoulos, C. Allen, E. W. Anderson, H. Areti, V. Balamura, S. Banerjee, P. D. Beery, P. Bhat, J. M. Bishop, N. N. Biswas, A. Bujak, D. D. Carmony, T. Carter, P. Cole, Y. Choi, R. De Bonte, V. DeCarlo, A. Erwin, C. Findeisen, A. T. Goshaw, L. J. Gutay, A. S. Hirsch, C. Hojvat, J. R. Jennings, V. P. Kenney, C. S. Lindsey, C. Loomis, J. LoSecco, T. McMahon, A. P. McManus, N. Morgan, K. Nelson, S. H. Oh, J. Piekarz, N. T. Porile, D. Reeves, A. Rimai, W. R. Robertson, R. P. Scharenberg, R. Stampke, B. C. Stringfellow, M. Thompson, F.

Turkot, W. D. Walker, C. H. Wang, J. Warchol, D. K. Wesson, and H. Zuong, (In Press, Phys. Rev. D.)

- [4] **Hyperon Production from $p - \bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV**, T. Alexopoulos et al., Phys. Rev. D**46**, 2773, 1992.
- [5] **Results from E-735 at the Tevatron Proton-Antiproton Collider with $\sqrt{s} = 1.8$ TeV**, T. Alexopoulos et al., Nuclear Phys. A**544**, 343c (1992).

Abstracts

- [6] **Search for Quark-Gluon Plasma in $p - \bar{p}$ Collisions**, N. T. Porile, Abstracts Div. Nucl. Chem., Am. Chem. Soc., August 1992.
- [7] **Physics Capabilities of the EOS-TPC**, E. Hjort, et al, Bull. Am. Phys. Soc. **37**, 1265, 1992.
- [8] **Collective Flow in Ca+Ca at 800 MeV/nucleon and Au+Au at 400 MeV/nucleon**, M.D. Partlan et al., Bull. Am. Phys. Soc. **37**, 1266, 1992.
- [9] **High Order Collective Flow Correlation in EOS-TPC Data**, Y. Shao et al., Bull. Am. Phys. Soc. **37**, 1266, 1992.
- [10] **Event-by-Event Flow Fluctuations in Central Au+Au Collisions**, S. Wang et al., Bull. Am. Phys. Soc. **38**, 998, 1993.
- [11] **High Order Collective Flow Correlations in Heavy Ion Collisions**, Y. Shao et al., Bull. Am. Phys. Soc. **38**, 999, 1993.
- [12] **Collective Flow in Au+Au from 250 MeV/nucleon to 1200 MeV/nucleon**, M.D. Partlan et al., Bull. Am. Phys. Soc. **38**, 999, 1993.

7. References

- [1] T. Alexopoulos et al., Phys. Rev. D**46**, 2773 (1992).
- [2] V. V. Goloviznin et al., Z. Phys. C**38**, 255 (1988).
- [3] T. Alexopoulos et al., Phys. Rev. D (in press).
- [4] A. Shot, Phys. Rev. Lett. **54**, 1122 (1985).
- [5] T. Sjostrand and M. Zijl, Phys. Rev. D**36**, 2019 (1987).
- [6] J. E. Finn, et al., Phys. Rev. Lett. **49**, 1321 (1981); R. W. Minich, et al., Phys. Lett. **B118**, 458 (1982); A. S. Hirsch, et al., Phys. Rev. C**29**, 508 (1984).
- [7] X. Campi, J. Phys. A: Math. Gen. **19**, L917 (1986); X. Campi, Phys. Lett. **B208**, 351 (1988).
- [8] E. Gatti, A. Longoni, H. Okuno and P. Seemenza, Nucl. Inst. Meth. **163**, 83 (1979).
- [9] E. Mathieson, Nucl. Instr. Meth. **A270**, 602 (1988).
- [10] D. L. Fancher and A. C. Schaffer, IEEE Transactions on Nuclear Science, **NS-26**, 150 (1979).
- [11] A. Sobel, E. Hjort, H. Z. Huang, P. Jones, J. Mitchell, and H. Wieman, STAR note 88 (1992).

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