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

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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 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.

1.2 1992 Milestones

The Purdue High Energy Nuclear Physics group had the sole responsibility for the analysis of the CTC data. This required the development of sophisticated pattern recognition algorithms and criteria for identifying 'primary' tracks, i.e., those tracks originating from the beam-beam interaction. Graduate student Charles Allen has played the leading role in this project. His Ph. D. thesis, entitled "Multiplicity and Pseudorapidity Distributions from Proton-Antiproton Collisions at Center of Mass Energy 1.8 TeV" was completed in December 1991. Below we briefly discuss some results from his analysis.

The two major quantities the CTC measures are multiplicity and the pseudorapidity density in the range $|\eta| \leq 1.6$. The multiplicity is independently measured by a scintillator hodoscope that covers the range $|\eta| \leq 3.5$ but with a much coarser grain. The CTC is able to resolve two tracks separated by 3 mm in the xy plane. In terms of multiplicity, the CTC is able to measure total charged multiplicity in the CTC up to approximately 100.

For the multiplicity analysis, approximately 150,000 minimum bias events were used. Two separate algorithms were implemented to extract the true multiplicity into the CTC volume, giving the results shown in Figure 1.

The CTC measures the z coordinate by charge division. For mechanical reasons, a relatively low resistance (190 Ω/m) sense wire material was used. This limited the intrinsic

Figure 1 Charged primary multiplicity into the CTC volume.

z resolution to approximately 4 cm, compared to a minimum lever arm of approximately 10 cm. In addition, capacitive crosstalk between the sense and field wires introduced a systematic shift in the measured z . A correction was developed that works at a statistical level, but it is still unclear how well it works on a track by track basis. The result is that the z coordinate of hits, and hence the pseudorapidity of tracks, is not well known. Still, one can calculate the pseudorapidity density as a function of pseudorapidity. The value at $\eta = 0$ is expected to be fairly good, since the z correction is minimal there. Figure 2 shows what the CTC measures for $\frac{dN}{d\eta}$ versus η .

A second major analysis effort has been conducted by Philip Cole, our graduate student based at Fermilab. He has analyzed spectrometer information and is examining the re-

Figure 2 Pseudorapidity density in the CTC vs. pseudorapidity.

relationship between $\langle p_t \rangle$ and multiplicity for pions and antiprotons. He has analyzed approximately 15 million events, using both the Fermilab Amdahl and Vax cluster computers. A large part of this analysis involves corrections for the geometrical acceptance of the spectrometer, tracking inefficiencies, and other subtle effects. We have used the GEANT simulation of the experiment to study these effects and to correct the data. The corrections are substantial for the lowest p_t bin measured. After the above corrections have been applied, the average transverse momentum can be computed as a function of the multiplicity interval. The multiplicity has been measured using two different devices, the scintillator hodoscope and the Central Tracking Chamber. Shown in Figures 4 and 5 are $\langle p_t \rangle$ vs. charged

rapidity density for various particle species. These results comprise the major portion of Philip Cole's Ph.D. thesis which was completed in December, 1991.

1.3 Forthcoming and Future Publications

Below we list papers which are pending publication and those which will be submitted for publication in the near future.

- **Mass Identified Particle Production in Proton-Antiproton Collisions at $\sqrt{s} = 300, 540, 1000, \text{ and } 1800 \text{ TeV}$.** This paper discusses the behavior of the transverse momentum spectra for pions, charged kaons, and antiprotons as a function of $\sqrt{s}$ and charged particle multiplicity. Using the Bjorken formula for estimating the energy density, ϵ , from the observed charged particle multiplicity and the mean transverse momentum, it is estimated that we have observed events in which $\epsilon \sim 6 \text{ GeV/fm}^3$. This paper will be submitted to Physical Review D.
- **Hyperon Production from Proton-Antiproton Collisions at $\sqrt{s} = 1.8 \text{ TeV}$.** The production of hyperons as a function of charged particle multiplicity and transverse momentum is studied. The $\langle p_t \rangle$ for lambdas was found to be about 0.75 GeV/c and for cascades about 0.90 GeV/c . The production of lambdas relative to protons is approximately constant as a function of both $\sqrt{s}$ and multiplicity. This latter result is much different from that observed in heavy ion experiments. This paper has been submitted to Physical Review D.
- **Particle Production in Antiproton-Proton Collisions at 300, 1000, and 1800 GeV Center-of-Mass Energy.** Charged pion, kaon, and proton-antiproton production, is studied as a function of transverse momentum and charged particle multiplicity.

The average transverse momentum of pions as a function of multiplicity is shown to behave differently than protons. This paper will be submitted to Physical Review D.

- **Charged Particle Multiplicity Distributions in Proton-Antiproton Collisions at $\sqrt{s} = 0.3, 0.546, 1.0,$ and 1.8 TeV .** Non-single diffractive multiplicity distributions are studied for the pseudorapidity intervals of $|\eta| < 1.62$ and $|\eta| < 3.25$ and for full phase space. These results are compared to those from other experiments. This paper will be submitted to Physical Review D.
- **A Study of Source Size in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV Using Pion Interferometry.** Using Bose-Einstein correlations between pairs of identical pions, the source size and lifetime have been estimated. Both the dimension along the incident $p\bar{p}$ direction and the lifetime depend strongly on pion multiplicity. For the entire data sample studied, the average value of the source size is about 1.06 fm and its lifetime is 0.74 fm/c. The degree of coherence of the source of pions increases as pion multiplicity increases. This paper has been submitted to Physical Review D.
- **Photon Production at $\sqrt{s} = 1.8$ TeV .** This paper will discuss the production of low energy photons in proton-antiproton collisions. An excess of low energy photons has been observed.
- **Phi Production at $\sqrt{s} = 1.8$ TeV .** Phi production as a function of charged particle multiplicity will be presented.
- **Forward-Backward Correlations at $\sqrt{s} = 1.8$ TeV .** An analysis of forward-backward correlations will be presented. This work is still in progress.

- The Production of K_s^0 and K^* at $\sqrt{s} = 1.8$ TeV . This work is still in progress.
- Low Transverse Momentum Pions. This work is still in progress.
- Deuteron and Triton Production at $\sqrt{s} = 1.8$ TeV . This work is still in progress.

2. An Exclusive Study of Nuclear Fragmentation using the EOS-TPC

2.1 The Search for Critical Phenomena using the EOS-TPC.

The Purdue High Energy Nuclear Physics group has initiated an experimental program to study multifragmentation at the Lawrence Berkeley Laboratory Bevalac. Heavy projectile beams at 1 GeV/nucleon will bombard light targets. The resulting projectile fragments will be detected in a Time Projection Chamber, TPC, and other ancillary detectors, permitting the determination of the charge and momentum of all of the interaction products on an event-by-event basis. The unique features of this 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 velocity and are carried forward into the TPC.
- the development of a new detector, the Equation Of State (EOS) TPC. This device is being built by the Relativistic Nuclear Physics group at LBL.
- the characterization on an event-by-event basis of the nature of the interaction.

This last point is detailed below.

The Purdue High Energy Nuclear Physics group has a long history of working in the field of nuclear fragmentation. Our previous inclusive studies have led us to suggest the analogy between nuclear fragmentation and a liquid-gas phase transition occurring in a van der Waals gas. Recently, Campi has analyzed 400 exclusive gold-emulsion events and concluded that nuclear fragmentation has the characteristics of a critical phenomenon. The experiment we will conduct at the Bevalac will allow us to extract the critical exponents

describing the phase transition. Using the EOS-TPC and a Multiple Sampling Ionization Chamber (MUSIC), the momentum and charge of each projectile fragment will be determined. Events can then be characterized as subcritical, critical, or supercritical. In addition, we will employ a time-of-flight wall (TOF) in order 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 has been added. See Figure 3. Further physics details can be found in our proposal submitted to LBL.

Experimental layout

Figure 3

Our experiment is part of a larger program of the EOS-TPC group, of which the Purdue High Energy Nuclear Physics group is a part. In fact, we are participating in two additional experiments, both of which concentrate on flow effects in nuclear matter at Bevalac energies. All of these experiments will begin running in the latter half of 1992. At present we have three graduate students, James Elliott, Mark Gilkes, and Penny Warren, who will obtain Ph. D. theses from the fragmentation experiment. In addition, Eric Hjort, a post doctoral research assistant is stationed at LBL to participate in the hardware and software development of the EOS-TPC system.

The primary responsibilities of the Purdue High Energy Nuclear Physics group are:

- design, testing, and installation of the beam line between the last quadrupole magnet and the TPC entrance. This includes beam-locating scintillation detectors and a gas ionization detector to distinguish beam particles from multifragmentation interaction products. The beam line will be used in all of the TPC experiments. This work has been done at both Purdue and LBL.
- debugging and maintaining the MUSIC and TOF detectors.
- simulations for calculating track reconstruction efficiencies. This is on-going at Purdue.
- Development of track matching algorithms for various detectors.
- development of analysis techniques for extracting the critical indices from the data. This work is nearing completion.
- participating in the other two (at present) TPC experiments. This will include running shifts, maintaining detectors, and analyzing data.

The three TPC proposals were accepted by the PAC at LBL in June 1990. The experiments will begin data taking in July 1992.

2.2 Results of the 1992 Test Runs

Over two weekends in March and April 1992, the full EOS-TPC detector system was tested using beams of gold, calcium, neon, and alpha particles. The total running time was about 200 hours. Of this, nearly 16 hours were spent calibrating the MUFFIN detectors and the TOF wall.

The results from these test runs have been useful in preparation for the block running time this summer. Several problems in the TOF wall were diagnosed and have been corrected. Results from the MUSIC detector indicate its capability for single charge resolution. Figure 4 shows charge versus distance in mm from the anode for particles obtained in Ca + Ca collisions at 800 MeV/nucleon. The physical edge of the cathode resides at 500 mm. Events at distances greater than 500 mm are unphysical. These are uncalibrated data from one brief test run.

A small sample of data was obtained from 400 MeV/nucleon Au + Al collisions. Approximately 100 tracks in the TPC were reconstructed and a very preliminary sphericity-coplanarity analysis performed on this data. High statistics will permit the study of the event shape through such an analysis as a function of the event multiplicity. The correlation between the event shape and the behavior of the moments of the fragment charge distribution should prove to be very informative.

Figure 4

2.3 Nucleus-Nucleus Collision Simulations

During the past year we have made significant progress developing an appropriate

event simulator of heavy ion collisions at relativistic energies. One of the main obstacles we faced was the fact that most heavy ion simulators do not create a realistic spectrum heavy nuclear fragments. To remedy this situation in a manner which was computationally feasible, we have “mated” two different programs. The first is an internuclear cascade calculation performed by ISABEL, a well-known nucleus-nucleus event generator. This program produces knockout nucleons and pions from both projectile and target, leaving excited projectile and target remnants. The second stage is a statistical multifragmentation code which deexcites both excited remnants. The resulting distribution of particles can then be tracked through our apparatus and tracking efficiencies estimated. Our results indicate that the combination of TPC plus TOF detectors are capable of observing approximately 75% of the multiply charged particles $2 \leq Z \leq 6$ for 1 GeV/nucleon Au + C. The TPC efficiency for $Z = 1$ is about 90%, while MUSIC’s efficiency for $Z > 6$ is 100%. The net effect of these inefficiencies on the determination of the moments of the fragment distribution is minimal.

2.4 Extraction of Critical Indices from Small Percolation Lattices

Previous inclusive studies have suggested the analogy between nuclear fragmentation and a liquid-gas phase transition in a van der Waals gas.[1] Campi analyzed exclusive gold-emulsion events by comparing the moments of percolation simulations and the moments of the data. He concluded that nuclear fragmentation has the characteristics of a critical phenomenon.[2]

In modern phase transition theory, all physical quantities depend on the critical exponents: α , β , γ , σ , and τ . With any two, we can derive the others. We can extract these critical exponents by exploiting the properties of the moments:

$$M_k = \sum_s s^k n_s \quad (1)$$

For percolation lattices:

$$M_2 \propto |p - p_c|^{-\gamma} \quad (2)$$

thus γ can be determined by plotting $\log(M_2)$ vs. $\log|p - p_c|$, where M_2 is the second moment and $|p - p_c|$ is the probability minus the critical probability, and determining the slope. Problems arising due to the finite size of the lattices can be alleviated by altering the value of p_c from its theoretical value.

An exclusive nuclear fragmentation experiment will not explicitly determine a probability, p , so the above method will not work directly. However, taking advantage of the approximately linear relationship between M_0 (or M), the multiplicity, and p in the critical region, i.e., $p \approx aM + b$, we substitute M for p in equation (2):

$$M_2 \propto |M - M_c|^{-\gamma} \quad (3)$$

Plotting $\log(M_2)$ vs. $\log|M - M_c|$ and determining the slope would determine the critical exponent γ .

Similar methods apply for determining β :

$$P \propto |p - p_c|^\beta \quad (4)$$

therefore:

$$P \propto |M - M_c|^\beta \quad (5)$$

Plotting $\log (P)$, where P is the largest cluster, or the largest fragment, vs. $\log |M - M_c|$ and determining the slope yields β .

The critical exponent τ can also be determined in a more straight forward manner. In general, equation (2) is written as:

$$M_k \propto |p - p_c|^{\left(\frac{\tau - k - 1}{\sigma}\right)} \quad (6)$$

Plotting $\log (M_3)$ vs. $\log (M_2)$ and computing the slope we find:

$$\frac{\Delta \log (M_3)}{\Delta \log (M_2)} = \frac{4 - \tau}{3 - \tau} \quad (7)$$

which does not directly depend on the probability.

An important issue which we are currently addressing is how to extract the critical exponents from nuclear fragmentation data. To this end, we have first attempted to use the above methods to extract the critical indices from small percolation lattices. By studying the behavior of the above relations in small lattices, we have been able to develop a systematic procedure for the extraction of the critical exponents. Our studies indicate that it should be feasible to extract the critical indices from the experimental data.

2.5 Results from 1992 Physics Run

After the series of test runs was completed in April, block physics running commenced in July 1992. This period lasted for six weeks, during which data was acquired for both the fragmentation experiment and the flow experiments. The approximate number of events for each beam and target combination is shown in the table below. A total of 450 high density 8 mm tapes were written at high density. A second block running period will commence in October and end in late November.

Table 1. July-September Running Statistics

Beam	Target	GeV/ nucleon	Number of events (thousands)
La	C	1000	50
Kr	C	1000	300
Kr	Al	1000	100
Au	C	1000	350
Au	Au	1000	200
Au	Au	800	236
Au	Au	600	246
Ni	Cu	1900	250
Ni	Au	1900	63
Ni	Cu	1500	179

Shown in Figure 5 and Figure 6 are some examples taken from on-line displays of data for the TPC and for MUSIC for 1 GeV/nucleon lanthanum incident on a carbon target. Note the excellent charge resolution obtained in the MUSIC detector. In Figure 7 we show the correlation between the total reconstructed charge in the TPC versus the charge of the largest fragment found in MUSIC for 1 GeV/nucleon gold incident on carbon. The vertical axis scale is set by dividing the total charge in the TPC by gold's charge, 79.

Analysis of the data from the first run has begun. This will be a lengthy process, with most of the time consumed by the TPC hit finder. Having found hits, tracks are formed. This process holds for the MUSIC detector as well. Ultimately, tracks from the TPC and MUSIC will be matched to hits in the TOF detector.

Figure 5 Time Projection Chamber On-Line Display

Figure 6 MUSIC Detector On-Line Display

2.6 Time Line

- Installation of TPC and beamline

Oct.-Nov. 1991 (completed)

Figure 7 Total charge in TPC vs. charge of largest fragment in MUSIC.

- Testing of TPC

Nov. 1991 (completed)

- **Final test runs** **Mar.-April 1992 (completed)**
- **Fragmentation experiment block running time** **July-Sept. 1992 (completed)**
- **Second block running time** **Oct. - Dec. 1992**

3. Soft Photons at the AGS

Experiment E855 ran at the AGS in 1990. A group from ORNL (including M. Tinnick, now at Purdue), C. Woody of BNL, C. Erd of Vienna, and R. Clark of Vanderbilt comprised the experimental collaboration. 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 [3]. The SPS experiment recently 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. See Figure 8.

Analysis of the E855 results from the AGS continues. Monte Carlo studies are almost complete to give factors for photon efficiency, energy resolution and leakage, and geometrical corrections. A theoretical analysis of the expected bremsstrahlung yield has been made. A deconvolution of the single photon spectra to identify the π^0 background is under

Figure 8 Inclusive photon transverse momentum spectrum from 450 GeV/c p+Be collisions at the SPS. The falling curve at the right is the calculated hadronic bremsstrahlung spectrum, and the rising curve in the middle is the deconvolved photon distribution from π^0 decay. Within errors, no source of excess photons is claimed.

way. The photon rapidity and transverse momentum spectra are beginning to assume their final form. Limits on or a claim of excess soft photons will be available from these data by the end of 1992. 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 1993. A Physical Review Letter will also be submitted in early 1993. A further paper on photons from nuclear de-excitation in p+W collisions is anticipated for later that year. This will complete experiment E855.

4. Solenoidal Tracker at RHIC

The Solenoidal Tracker at RHIC (STAR) is an experiment planned to commence operation in fall 1997 at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL). STAR will study the high density, high temperature state of matter formed in the collisions of heavy nuclei at relativistic energies. It will attempt to identify almost all of the charged hadrons produced in the central rapidity region of these reactions, using a large Time Projection Chamber (TPC). The experimental configuration is shown in Figure 9. The primary physics goals of this experiment are to study the thermodynamics of large hadronic systems, and to search for a new state of matter: the Quark Gluon Plasma (QGP). STAR will also be able to investigate parton structure functions and spin correlations in polarized proton-proton collisions, as proposed by the RHIC Spin Collaboration.

In June 1992, the STAR Collaboration produced its Conceptual Design Report (CDR), and submitted it to the RHIC Technical Advisory Committee at BNL [4]. This document details the component detectors of the STAR experiment, explains their capability to achieve the physics goals stated in the STAR proposal, and presents a comprehensive breakdown of the schedule and responsibilities needed to complete the construction of the experiment by fall 1997. One of the salient features of the CDR is a phased deployment schedule for some of the component detectors within STAR, dictated by cost constraints. The central Time of Flight (TOF) system and the External Time Projection Chambers (XTPCs) have been deferred until a second phase after 1997, when extra DOE construction funds may become available. Funding outside the DOE RHIC construction budget is being sought for the Silicon Vertex Tracker (SVT), and the Electromagnetic Calorimeter (EMC), with the hope they will be in phase one in 1997. Obviously, delay of any of these elements

Figure 9 Solenoidal Tracker at RHIC

limits the physics reach of the experiment, but these staging choices preserve the essential core of the proposed experiment: the large (2 m radius x 4.2 m long) central TPC, solenoidal magnet, trigger detectors, data acquisition system, and computer analysis facility. The CDR also contains much more detailed analyses and simulations of detectors' performance, and a keener assessment of its physics capabilities. In addition, the organization and management structure of the collaboration is maturing rapidly, underpinning the success of this 5 year, \$30M effort. The BNL Technical Advisory Committee endorsed the STAR CDR in August 1992. The last hurdle before STAR becomes a full DOE project is the BNL Program Advisory Committee's approval of the physics program; this is expected in October 1992.

In 1992, the Purdue High Energy Nuclear Group participated in several working groups within STAR. The largest effort was assisting in the design of the TOF system. A major breakthrough came from H. Huang's suggestion to use magnetically tolerant mesh dynode photomultipliers (PMTs) to readout short scintillator "shingles" tiling the barrel region around the central TPC. (Huang was then at LBL; he joins Purdue in January 1993.) This solves (in principle) the issue of timing with resolution better than 100 ps in a 0.5 T magnetic field. A complete TOF design was developed by several members of the TOF working group (including Purdue), involving 7776 shingle elements mounted on rails on the Outer Field Cage of the TPC. Recent tests and simulations by Rice University predict a time resolution (sigma) of 64 ps, and a particle identification efficiency for high multiplicity Au+Au events of >75%.

Unfortunately, the estimated cost of this system is \$9M, and it has been dropped from phase one of STAR. Instead, a Central Trigger Barrel (CTB) using about 400 PMTs and

large scintillators is planned to cover the TPC, because of the obvious need for a multiplicity trigger in the central region. The CTB is designed to be mechanically compatible with the TOF system, so the large multiplicity scintillators can be replaced in patches with finely segmented TOF shingles as funding permits.

M. Tincknell and Purdue undergraduate physics major T. Keaffaber have done several Monte Carlo simulations to study aspects of the STAR TOF design. In late 1991, they checked the efficacy of a novel TOF system proposed by P. Lindstrom of LBL. Although their study indicated that Lindstrom's scheme would work, it lost out to the more conservative shingle design, before the whole TOF project was suspended. Subsequently, in 1992 they have worked to develop simulations of optical pulse propagation in scintillators. This effort will focus on the most accurate way to count charged particles that will hit the large scintillator bars in the CTB. This investigation will combine both simulations and laboratory results, and will be Keaffaber's Senior Thesis project.

Since summer 1992, Purdue has become involved TPC R&D, and plans for production testing of the TPC pad plane sectors. Purdue is also working with the Trigger and Data Acquisition groups to design the architecture of those systems. R. Scharenberg helped write the STAR CDR, particularly the Trigger section. Purdue plans to contribute significant effort to STAR throughout the rest of the decade.

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

In 1991, the Purdue High Energy Nuclear Group initiated 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 in the first year of this project is the demonstration of feasibility: AVDs have been shown to be directly sensitive to minimum ionizing particles with a useful signal-to-noise ratio, and 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.

The AVDs which have been tested to date were custom modules purchased from EG&G Optoelectronics Division, Montreal, Canada (contact: R. McIntyre). The sensitive area of these diodes is $5 \times 5 \text{ mm}^2$, and they have an effective thickness of $120 \text{ }\mu\text{m}$. The modules include a preamplifier. The diodes have an operating voltage of $\sim 400 \text{ V}$ and an internal avalanche gain of ~ 50 .

The principle of the first tests was to make basic measurements using facilities available at Purdue. 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 10.

The signal is created in the diodes by the ionizational 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 $\sim 1 \mu\text{m}$ thick. This initial 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 fast constant fraction discriminator (CFD). Start and stop from the CFDs were fed into a Time to Pulse Height Converter), which then fed a shaped pulse into a peak-sensing ADC.

5.1 Expected AVD Signals

A simple and accurate estimate of the expected AVD signal characteristics can be made. The average energy lost of a minimum ionizing particle in $120 \mu\text{m}$ of Si is about 45 keV, so each β^- produces about 12,500 electron-hole pairs. After the subsequent amplifications, the expected output is 7.5×10^8 electrons. The signal rise and fall times should be $t_{\text{rise}} \equiv t_{\text{fall}} \equiv 2.5 \text{ ns}$, and the FWHM should be $t_{\text{FWHM}} \equiv 5 \text{ ns}$. The peak current is expected to be $\sim 24 \text{ mA}$ (7.5×10^8 electrons in 5 ns), corresponding to an expected $\sim 1.2 \text{ V}$ 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. Both Vavilov and gain nonuniformity variations can be corrected with a constant fraction discriminator. The dominating source of signal fluctuations is the preamplifier noise; the expected noise is 20 mV RMS. Since the

Silicon Avalanche Diode R&D Block Diagram

Figure 10

noise fluctuates positive and negative, this gives an expected signal-to-noise ratio of $1200 \text{ mV} / (2 \times 20 \text{ mV}) \cong 30$. The observed preamplifier noise is fully consistent with these expectations.

The expected time resolution can be estimated directly from the risetime and signal-to-noise ratio. For a leading edge discriminator (LED), the time for a linearly-rising signal will cross a fixed threshold will vary simply as (risetime)/ (signal-to-noise). This is $(2.5 \text{ ns}) / 30 \cong 85 \text{ ps}$.

5.2 Experimental Results

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

The time spectrum of two AVDs with β^- pulses in coincidence was taken with CFDs and a TPHC-ADC system with 5.37 ps/channel and $\sim 9 \text{ ps}$ intrinsic time dispersion. The data were fitted with a Gaussian. Since each diode contributes equally (approximately) to the variance, the effective resolution of an individual diode is $\sigma/2^{1/2} = 80 \text{ ps}$.

In another experiment, the trigger events were selected with pairs of leading edge discriminators (LEDs) defining a lower and an upper amplitude window for each AVD signal. The timing start and stop signals were discriminated with CFDs as usual, and the resulting fitted single diode time dispersion was $\sigma = 65 \text{ ps}$. This indicates that careful amplitude walk

correction of time signals generated from LEDs might improve the time resolution to $\sigma < 65$ ps. See Figure 11.

The time resolution does not vary strongly as a function of temperature or voltage. This implies that AVD TOF detectors will probably not require expensive or difficult stabilization of either V_{bias} or temperature.

AVDs have delivered their promised time resolution in a small laboratory experiment. 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.

Figure 11 AVD Time Resolution

6. References

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