DOE/ER/040309-13

U. S. DEPARTMENT OF ENERGY
GRANT No. DE-FG05-87ER40309

NUCLEAR STRUCTURE AT INTERMEDIATE ENERGIES

PROGRESS REPORT

for

January 1-December 31, 1990

PRINCIPAL INVESTIGATORS

B. E. Bonner
G. S. Mutchler

T. W. Bonner Nuclear Laboratory
Physics Department
RICE UNIVERSITY
Houston, Texas 77251-1892

September 30, 1990

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED
MASTER *pr*

NUCLEAR STRUCTURE AT INTERMEDIATE ENERGIES

1. Project Abstract and Overview

We report on the enormous amount of progress made during this contract period. The theme that unites the sometimes seemingly disparate experiments undertaken by the Bonner Lab Medium Energy Group is a determination to understand in detail the many facets and manifestations of the strong interaction, that which is now referred to as non-perturbative QCD. Whether we are investigating the question of just what does carry the spin of baryons as in the CERN SMC experiment, or the extent of the validity of the SU(6) wavefunctions for the excited hyperons as will be measured in their radiative decays in our CEBAF experiment, or questions associated with the formation of a new state of matter predicted by QCD, the so-called Quark Gluon Plasma, the subject of our BNL experiments E810, E854, and a RHIC Letter of Intent, - all these projects share this common goal. Our other experiments represent different approaches to the same broad undertaking. LAMPF E1097 will provide definitive answers to the question of the spin dependence of the inelastic channel of pion production in the $n - p$ interaction. FNAL E683 may well open a new field of investigation in nuclear physics: that of just how quarks and gluons interact with nuclear matter as they traverse nuclei of different sizes. In all the experiments mentioned above, the Bonner Lab Group is playing major leadership roles as well as doing a big fraction of the hard work that such experiments require. We use many of the facilities that are available to the intermediate energy physics community and we use our expertise to design and fabricate the detectors and instrumentation that are required to perform the measurements which we decide to do.

The format we follow in both the Progress Report and the Proposal is to have a brief writeup on each individual experiment or project and to include in the appendices copies of published papers or manuscripts which give much greater detail. The aim is to concentrate on the physics goals, the results, and their significance in the main body of the report.

Table of Contents

1.	Project Abstract and Overview	i
2.	Personnel List	iii
3.	PROGRESS ON RESEARCH PROJECTS	1
A.	Brookhaven AGS Experiments	1
(1)	BNL E854: Antiproton Nucleus Interactions	1
(2)	BNL E810 - Strangeness Production in Heavy Ion Collisions	3
(3)	BNL E818, Search for a J^{PC} Exotic Hybrid Meson	7
B.	CERN NA47: The SMC Experiment	9
C.	LAMPF and TRIUMF Experiments	10
(1)	Introduction	10
(2)	TRIUMF E372: Pion Production in $\bar{n}p$ Scattering	10
(3)	LAMPF E876: Spin Transfer Measurements for $\bar{n}p$ Elastic Scattering	10
(4)	LAMPF E1097: Pion Production in $\bar{n}\bar{p}$ Scattering	10
(5)	TRIUMF E452: Radiative Muon Capture (RMC) on Hydrogen	11
D.	CEBAF PR-89-024: Radiative Decays of Low-Lying Hyperons	12
E.	FNAL E683: Photoproduction of Jets in Nuclei	15
F.	Instrumentation Projects	19
(1)	Cylindrical Multiplicity Detector for BNL E854	19
(2)	MWPC Detectors and Electronics for CERN NA47	22
(3)	Lead Glass Array for CERN NA47	22
(4)	Cylindrical Wire Chamber for LAMPF E1097	22
(5)	Beam Calorimeter for FNAL E683	24
(6)	Shower Counter for BNL E818	25
(7)	Muon Veto Hodoscope for FNAL E683	26
4.	Changes in Personnel	26
5.	1990 Publications, Presentations, & Theses	27
6.	COPIES OF SELECTED PUBLICATIONS and MANUSCRIPTS	29
E810: "Modular TPCs for Relativistic Heavy-Ion Experiments," A. Etkin, B. E. Bonner, G. S. Mutchler <i>et al.</i> , Nuclear Instruments and Methods A283 , 557 (1989).		
E817: "Analyzing Power of Inclusive Production of π^+ , π^- and K_S^0 by Polarized Protons at 13.3 and 18.5 GeV/c," B. E. Bonner, F. Nessi-Tedaldi <i>et al.</i> Physical Review D41 , 13 (1 January 1990).		
E854: "Strangeness Production in Antiproton-Tantalum Interactions at 4 GeV/c," W. R. Gibbs and J. W. Kruk, Physics Letters B237 , 317 (22 March 1990)		
E810: "Neutral V Production with 14.6 x A GeV/c Silicon Beams," S. E. Eiseman, B. E. Bonner, G. S. Mutchler <i>et al.</i> , submitted to Physics Letters B, May 30, 1990.		

D.O.E GRANT No. DE-FG05-87ER40309

NUCLEAR STRUCTURE AT INTERMEDIATE ENERGIES

2. Personnel List

Personnel working on the project January 1, 1990-December 31, 1990:

PROFESSORS OF PHYSICS

B. E. Bonner, Chairman, Physics Department
G. S. Mutchler

RESEARCH SCIENTIST

Salahuddin Ahmad (Ph.D., University of Victoria)

GRADUATE RESEARCH ASSISTANTS

D. W. Lincoln (M.A., Rice University)
M. M. Traynor (M.A., Rice University)
C-N Chiou (M.A., Rice University)
J. P. Cummings (M.A., Southeastern Massachusetts University)
T. L. Gaussiran (B.S., University of Texas at Austin)
S. L. Eichblatt (B.A., Royal Melbourne Institute of Technology)
A. Empl (Vordiplom, Friedrich-Wilhelms University)
G. P. Morrow (B.S., University of Notre Dame)

Rice Undergraduate Summer Lab Assistants

Michael Henry, Paul Phillips, Renee Beveridge, & Sharon Casteel

STAFF

J. A. Buchanan (B.S., University of Houston), Senior Research Engineer
J. M. Clement (Ph.D., Rensselaer Poly. Inst.) Research Engineer
Helen Viereck (M.A., University of Houston) Administrative Assistant

Visiting Scholar

Dr. Stoyan Toshkov (Ph.D. University of Sofia)

3. PROGRESS ON RESEARCH PROJECTS

A. Brookhaven AGS Experiments

(1) BNL E854: Antiproton Nucleus Interactions

The purpose of this experiment is to search for experimental signatures of the predicted formation of hot hadronic matter in the absorption of energetic antiprotons on a range of nuclei. This experiment probes the high temperature - low density region of the nuclear matter phase diagram and is complementary to the low temperature - high density region being studied in heavy ion experiments such as our AGS E810. In the only other experiment where $\bar{p}$ - nucleus interactions were studied at intermediate energies, Miyano *et al.*¹ used antiprotons of momentum 4 GeV/c to bombard tantalum plates mounted in a bubble chamber. The production cross sections of K_s^0 , Λ , and $\bar{\Lambda}$ and the rapidity distributions of K_s^0 and Λ were measured.

Strottman and Gibbs² have calculated $\bar{p}$ annihilations in nuclei with both hydrodynamic and nuclear cascade models. An extension of Gibbs' intranuclear cascade code (INC'), made at Rice,³ successfully reproduces all the features of Miyano's measurement. However, according to J. Rafelski,⁴ Miyano's results can also be interpreted as evidence of the formation of a Quark Gluon Plasma (QGP). In the INC one assumes a straightforward reaction model in which antiprotons deposit energy in the forward cone of nuclear matter within the target nucleus. The code predicts that for a momentum of 5 GeV/c, between 2%-5% of the interactions will result in the attainment of an energy density of 2.5 GeV/fm³ or greater; for 9 GeV/c, this fraction rises to 50%-90%, with the higher values for the heavier nuclei. For 9 GeV/c, about 10%-15% of the interaction will give energy densities of 3.5 GeV/fm³ or more. It is generally thought that interesting effects may be observed at energy densities above 2.5 GeV/fm³, which corresponds to a temperature of about 170 MeV. Such large energy densities could prompt a phase transition to a quark gluon plasma!

The first E854 engineering test run occurred at the Multi Particle Spectrometer (MPS) facility of Brookhaven National Laboratory in April, 1990. Antiproton beams of 5 and 9 GeV/c were used to interact with C, Cu, Al, Pb and CH₂ targets. In order to track the Λ , $\bar{\Lambda}$, K_s^0 decay particles, we used two seven-plane multiwire drift chamber modules in the upstream and five in the downstream region of the target as is shown in Fig.1. During the two weeks of beam time, we wrote about 120 data tapes. A typical event is shown in Fig.2.

For our experimental setup, the pattern recognition segment of the MPS analysis program has to be changed and optimized. A computer code using the program package GEANT of the CERN library was written to track particles of INC'-simulated events through the geometry of the detector and to create an output identical to our experimental raw data format. With this simulated data in addition to the experimental data, we are able to debug the MPS program to adapt it to our setup and in particular to tuneup the pattern recognition segment (the fit, cut parameters, etc.). Once the parameters are optimized, we will be in the position to analyze the data. All these activities are taking place at Rice.

Figure 1: Plan View of E854 Apparatus

1-7: Drift Chambers
A,B: TPX's

Target: Pb (0.5%)
Beam Momentum: 9 GeV/c
Projectile: $\bar{p}$

Figure 2: X-Y Views of Typical $\bar{p}$ -Pb Event

As can be seen from Figure 1, the setup we used for the test run does not detect particles emitted perpendicular to the beam, so our April data will not provide complete information about the multiplicity distribution from the $\bar{p}$ annihilations. Since this information may be very important, we have designed a large angle multiplicity detector to surround the target for use in our next run, currently scheduled for 4 weeks in May, 1991. This detector is described in the section on Instrumentation.

¹K. Miyano *et al.*, Phys. Rev. Lett. **53**, 1725 (1984) and Phys. Rev. **C38**, 2788 (1988).

²D. Strottman and W. R. Gibbs, Phys. Lett. **149B**, 288 (1984).

³W. R. Gibbs and J. W. Kruk, Phys. Lett. **237**, 317 (1990).

⁴J. Rafelski, Phys. Lett. **207**, 371 (1988).

(2) BNL E810 - Strangeness Production in Heavy Ion Collisions

The purpose of E810 is to look for a possible phase transition from hadronic to quark matter: the Quark Gluon Plasma (QGP). The production of strangeness in heavy ion collisions is generally regarded as one of the hadronic signals that may be indicative of the formation of a QGP; indeed, strange anti-baryon production should be an especially sensitive indicator of a QGP. In the present experiment, our interest is to study the strangeness production in heavy ion collisions using beams from the AGS.

During the run in June of 1989, we obtained data with three Time Projection Chambers (TPC) along with a well-tweaked Time of Flight hodoscope (TOF) to allow particle identification. We took data for a 14.6 GeV/A Si beam on a 125 micron Cu and a 25 micron Au target. The TPCs⁵ tracked the large number (up to 100 tracks!) of outgoing charged particles and the TOF⁶ system should enable us to pick out $\bar{\Lambda}$ s by measuring the antiproton TOF. A plan view of the apparatus and the reconstructed tracks in the TPC modules for a typical Si-Au interaction are shown in Figures 3 and 4 respectively. A time resolution of $\sigma = 150$ ps was achieved. A P vs beta plot for negative particles is shown in Figure 5. Although pion and kaon bands are clearly visible, there is no clear evidence for antiprotons. Only limited statistics are available for the 1989 run s.

Preliminary results for this run have been presented in several conferences⁷ and a letter⁸ has been submitted to Physics Letters B for publication. A brief summary of these results is presented here. From the tracking of the charged particles, the pseudorapidity distributions were calculated. The data covered the range $1.5 < \eta < 7.0$. Under the assumption of pion mass the rapidity distributions were calculated. These were found to be in good agreement with the results of BNL E802. The momentum spectra were calculated for positive and negative tracks from Cu and Au. There is a clear indication of less stopping power for the Cu target.

The transverse momentum spectra were parameterized to estimate the effective temperature formed in the interaction. This was found to be about 150 MeV for $p_t > 0.2$ GeV/c and a rapidity of 2. Without the p_t cut the temperature was reduced to 125 MeV. Both values decreased with increasing rapidity. Finally neutral Vee's were reconstructed to look for Λ 's and K's. Clear mass signals were found with the correct lifetimes. No $\bar{\Lambda}$

Figure 3: Plan View of E810 Apparatus

Figure 4: Three Dimensional View of Typical Si-Au Event

candidates were found above background. The neutral Vee production rate versus negative particle multiplicity (a measure of the effective number of collisions) is in good agreement with HIJET calculations for Λ 's but not for K's. Further details can be found in the copies of the publications appended to this report.

Figure 5: P vs. β Plot

Since the above conclusions were severely limited by the small data sample, additional data was taken in June 1990 for the 14.5 GeV/A Si beam on C, Si, Ti, Cu, Sn, and W targets. Thin targets ($< 3\%$ interaction length) were used to minimize secondary interactions, primarily pair production from π^0 decay. The trigger consisted of the following:

1. A beam defining Cherenkov counter upstream of the target (also used as TOF start counter);
2. Several beam halo counters to veto upstream interaction;
3. Interaction paddles behind the target (above and below the beam) to require interactions in the target; and
4. A rear veto counter behind the MPS magnet.

Pulse height cuts on this last counter were made to insure that no heavy ion fragments survived the interaction. The interaction counters and rear veto counter were used to insure that a central interaction had occurred. This was necessary to reduce the data rate from uninteresting processes. The experimental run in 1989 formed the basis for the M.A. thesis of Mr. C-N Chiou.

Several improvements were made in the equipment for the run this year. A system to reduce the TPC HV by 10% between beam spills reduced the DC current drawn by the chambers and resulted in more reliable operation. As a result, about an order of magnitude more data was taken in the 1990 run. Improvements in the TOF system were also made. The TOF start counter used 0.7 ns risetime Hamamatsu R2083 phototubes instead of the 2.0 ns risetime RCA 8575's used earlier. In addition a longstanding noise problem in the TOF hodoscope signal lines was tracked down and eliminated. It is hoped that these improvements will allow us to achieve the original design goal of $\sigma = 135$ ps. This, coupled with the significant increase in data sample size, should give a noticeable improvement in the mass resolution of the TOF system.

Data analysis for this run is currently underway. The offline data processing is carried out in two stages. In the first stage the TPC raw data is unpacked. The MPS group then uses a Fermilab ACP Mutli-Microprocessor system to process drift chamber data. All the reconstructed track and vertex data of each good event is written to a data summary tape (DST) along with the raw TOF ADC and TDC data. In the second stage, the various physical processes are analyzed. We use the DST's to analyze the TOF data to determine the mass of the particles reaching the TOF hodoscope, the goal being to identify antiprotons originating from $\bar{\Lambda}$ decays. This portion of the data analysis will be done at Rice, and will form the basis for the Ph. D. thesis of Mr. C-N Chiou.

⁵A. Etkin *et al.*, Nucl. Inst and Meth. **A233**, 557 (1989).

⁶C. Chiou, Rice University M. A. Thesis, 1990.

⁷For example, B. E. Bonner *et al.*, *Heavy Ion Physics at the AGS Workshop*, March 1990, AIP Conference Proceedings (to be published).

⁸S. E. Eisman *et al.*, "Neutral V Production with 14.6 x A GeV/c Silicon Beams," submitted to Physics Letters B.

(3) BNL E818, Search for a J^{PC} Exotic Hybrid Meson

The object of BNL E818 is to search for non $q\bar{q}$ states in the light quark meson sector. One possibility of a non $q\bar{q}$ state is one which includes gluonic degrees of freedom. These degrees of freedom are expected in QCD to give rise to two new spectroscopies, Hybrid⁹ and Glueball.¹⁰ Several models predict such spectra with the low lying states in the 700 to 3000 MeV mass range.

The search for gluonic degrees of freedom in hadron spectroscopy has so far been confined to that of glueballs. However, the endeavor has been less than conclusive because the isoscalar meson sector is relatively poorly known and in addition, the glueballs can mix with them. It is therefore advantageous to search for the gluonic excitations in mesons called hybrids (or meiktons or hermaphrodites) which can be thought of as the meson states with a $q\bar{q}$ in color octet combined with a "valence" gluon to form color-singlet physical states.⁹ Sum rule and flux tube models¹¹ predict that the lowest lying states are J^{PC} exotic and slightly higher in mass than the lowest lying glueballs. The cross section for hybrid production is expected to be about the same as that of ordinary mesons, but decay to a pair of $L = 0$ mesons is suppressed. In E818, we are investigating the production of $I = 1$, $J^{PC} = 1$ hybrid X(1900), which is predicted to decay to $\pi^- b_1$ and $\pi^- f_1$ final states. We are interested in one of these decays which was seen through the decay chain:

$$X(1900) \rightarrow \pi^- f_1(1285) \rightarrow \pi^- a(980) \rightarrow K^+ \bar{K}^0 \rightarrow \pi^+ \pi^- \quad (1)$$

In addition, we are also looking for the $K\bar{K}\pi^-$ system produced in the reaction:

$$\pi^- p \rightarrow K^+ \bar{K}^0 \pi^- n \rightarrow \pi^+ \pi^- \quad (2)$$

to investigate the E/π region (i.e., 1.3 to 1.6 GeV). The $E/f_1(1420)$ has recently been tentatively identified as a $J = 1^{++}$ state, but there is still some confusion about this. Although this is a non exotic state, it would be difficult to place it in the scheme of SU(3) nonet families, indicating a non $q\bar{q}$ state.¹² It has been suggested that the $E/f_1(1420)$ is either a 1^{++} bound state of $K^* \bar{K}$ at threshold,¹³ or a P-wave π orbiting an S-wave $K\bar{K}$ at the center.¹⁴

The E818 measurement was performed at the Multi Particle Spectrometer (MPS) of Brookhaven National Laboratory in January-February, 1990. Pion beams of 18 GeV were used to interact in a 60 cm liquid hydrogen target. The experimental arrangement is shown in Figure 6. The trigger included a RAM trigger system, for identification of the fast forward Kaon, which looked for coincidences of appropriate clusters in the proportional chamber P3, the scintillator hodoscopes H1 and Time-of-Flight (T1), and no signal from the corresponding section of the segmented cerenkov counter C1. A multiplicity increase by two between P1 and P2 was also included in the trigger which would signal the decay of a K^0 . A cylindrical drift chamber (PC) was used in the X(1900) trigger to demand a recoil proton coming out from the target, to reduce the background due to diffractive dissociation of the beam. For the $E/f_1(1420)$ trigger, it was demanded that no signal be present in PC. Drift chambers DC(1-7) were used for tracking in the magnetic field and hodoscope (H2) was used to provide an additional information in the event reconstruction.

Over 800 hours of data were taken during the course of the run. Analysis of the $X(1900)$ state is being done at BNL on two Silicon Graphics workstations. The $E/f_1(1420)$ state is being analyzed at Rice using our IBM RS6000 workstations. The project will form the basis for the M.A. and Ph.D. theses for Rice graduate student John Cummings.

⁹M. Chanowitz and S. Sharpe, Nucl. Phys. **B222**, 211 (1983); J. M. Cornwall and A. Soni, Phys. Lett. **B120**, 431 (1983); K. Ishikawa *et al.*, Z. Phys. **C21**, 167 (1983).

¹⁰F. E. Barnes, F. E. Close and S. Monaghan, Nucl. Phys. **B198**, 380 (1982); M. Chanowitz and S. Sharpe, Nucl. Phys. **B222**, 211 (1983); and E. Golowich, E. Haqq and G. Karl, Phys. Rev. **D28**, 160 (1983).

¹¹N. Isgur and J. Paton, Phys. Lett. **124B**, 247 (1983); N. Isgur, R. Kokoski and J. Paton, Phys Rev Letts. **54**, 869 (1985).

¹²S. U. Chung, BNL Report-43263, Sept. 1989, Invited talk given at the International Meeting on Physics at Kaon Factory for TRIUMF, Vancouver, Canada, held at Bad Honnef, W. Germany, June, 1989.

¹³D. Caldwell, *Workshop on Glueballs, Hybrids and Exotic Hadrons*, Brookhaven, 1988, AIP Conf Proc. No.185, ed. S. U. Chung, page 465.

¹⁴R. Longacre, BNL preprint, to be published in Phys. Rev. and as quoted in reference 12.

Figure 6: Plan View of E818 Apparatus

B. CERN NA47: The SMC Experiment

The measurement of the spin dependent structure functions of the proton and neutron is scheduled to begin April 7, 1991, a schedule which has been pushed earlier by a year! A partially upgraded EMC spectrometer and the existing polarized target will be utilized. A target sample containing polarized deuterium will be inserted for part of the run to make a rough first measurement of the neutron structure function. We will also make a first measurement of the muon beam polarization with only part of the entire polarimeter operational.

Most of the Rice effort has been concentrated on the design and construction of the muon polarimeter (Figure 7). Three test runs have taken place: November 1989, December 1989, and June-July 1990. Critical measurements relevant to the design have been made: the electron contamination in the muon beam downstream of the experiment has been measured, and the design of shower counters to detect and veto these electrons has been finalized; the ability of the downstream quadrupoles to refocus the beam through the polarimeter magnet has been studied; and a rough measure of μ -decays in the region defined by the shower vetos has been made, using a lead glass hodoscope borrowed from OPAL in the correct position downstream of the magnet. A μ -detector, consisting of scintillator hodoscopes and an iron shielding block was placed on the opposite side of the beam from the lead glass. The $\mu - e$ coincidences resulting from scattering the beam from an Fe target upstream of the magnet were observed. These data are now being analyzed. The number of "decays" and of " $\mu - e$ scatters" are about the expected number, so the polarimeter design looks solid. However, tracking of the scattered and decay particles in the chambers which we are constructing is clearly critical for a precision measurement of the beam polarization. The construction of the MWPCs and Pb glass wall needed for the muon polarimeter are discussed in the Instrumentation Section.

Figure 7: The Muon Polarimeter

C. LAMPF and TRIUMF Experiments

(1) Introduction

Bonner Lab researchers actively participated in three nucleon-nucleon experiments during the past year. These include LAMPF E876 to measure spin observables in elastic neutron-proton scattering and TRIUMF E372 and LAMPF E1097, both of which measure cross section and spin observables for the reaction $np \rightarrow pp\pi^-$. Our role in the analysis of LAMPF experiments 818, 1035 and 1072 has only been advisory but significant progress has been made in all three. All of these experiments contribute to the experimental determination of nucleon-nucleon elastic and inelastic interactions. These are interesting for testing models of the strong interaction and as an ingredient in the description of nucleon-nucleus scattering.

(2) TRIUMF E372: Pion Production in $\bar{n}p$ Scattering

For E372, we participated in a test run last January and in the first major data-taking run in September 1990. The experiment measures the cross section and analyzing powers using a polarized neutron beam on a liquid hydrogen target. The outgoing protons and sometimes the pion are detected in a pair of chambers followed by a scintillator array. The data from the the September run will be studied and if everything looks good, another run will take place in early November. This may be the final run.

(3) LAMPF E876: Spin Transfer Measurements for $\bar{n}p$ Elastic Scattering

In E876 we will measure a large number of spin observables in the elastic scattering of polarized neutrons from a liquid hydrogen target. The recoil protons are detected in an arm consisting of three MWPC's, a spectrometer magnet and the Janus recoil polarimeter. The scattered neutrons are detected in a second arm which is not required to fire for every event. All the parity-allowed spin observables involving the the incoming neutron and recoil proton will be determined. We participated in the installation of the experiment and the data-taking which began in late spring. Unfortunately, an accident in early July destroyed the hydrogen target and damaged many of the wire chambers. The detectors have been repaired and data will be taken with another target for a month this fall. The target will be repaired for more extensive running next spring and summer.

(4) LAMPF E1097: Pion Production in $\bar{n}p$ Scattering

Rice has continued to make a strong commitment to LAMPF experiment 1097. During the last year, we completed the design for the data acquisition electronics and continued the design and construction of a test chamber as well as the final cylindrical chamber. We are also heavily involved in the overall design and organization of the experiment. Two of the four spokesmen are at Rice and one is the project manager. We met with the LAMPF

management last spring and worked out an agreement for test running in 1991. We will construct our chamber by that time and LAMPF will provide electronics to instrument approximately a third of the wires. The chamber construction is being accomplished in collaboration with the University of Texas and our progress is detailed in the section on Instrumentation.

(5) TRIUMF E452: Radiative Muon Capture (RMC) on Hydrogen

This experiment aims to determine g_p , the induced pseudoscalar coupling constant of the hadronic weak interaction, by measuring the branching ratio for radiative muon capture (RMC) on hydrogen. While this process has been measured in complex nuclei, it has not yet been observed for hydrogen, due to the very low expected rate; about 6×10^{-8} of the muons stopping in a liquid hydrogen target will undergo RMC. The measurement is made using a large-volume drift chamber¹⁵ as a pair spectrometer to detect the photons from RMC. The expected precision on the branching ratio is 8%, which would yield a 10% measurement of the pseudoscalar coupling.

RMC data has been taken on a series of nuclear targets: Al, Si, Ca, Mo, Sn and Pb, and the analysis of these data is nearly complete. This information will be complementary to RMC data obtained earlier¹⁶ using the TRIUMF TPC and should shed light on the possibility of Z-dependent renormalization of g_p within the nucleus.

In May 1990, a new trigger scheme for the measurement on hydrogen was tested and debugged. This trigger required that only one of the leptons from the converted photon reach the outside of the drift chamber, and allowed an increase in the photon acceptance of about 50%. In addition, the spectrometer magnetic field was reduced from 2.7 to 2.4 kG, which also increased the acceptance. The increased data rate was reduced in software in a front-end microprocessor in the main FASTBUS crate, and the dead-time was thereby kept to an acceptable level (about 15%). In a three week run in July 1990, the first data on RMC on protium (isotopically enriched hydrogen) was obtained, and various backgrounds were studied. Backgrounds from radiative pion capture due to the residual pion contamination in the muon beam, and from muon capture on the walls of the target flask were measured to be at a manageable level. Muon-decay Bremsstrahlung, which could contribute to the signal due to any high-energy tail in the detector response function, was studied using a positive muon beam (from which no muon capture occurs), and was also found to be adequately low. These data are presently under analysis, but it appears that the single largest background will be due to cosmic-ray induced photons, which can be determined to high accuracy during beam-off periods. The experiment is scheduled to run again in December 1990, and February 1991. A paper on the entire RMC spectrometer is in preparation for Nuclear Instruments and Methods and a portion of that is presently being written at Rice. The Rice involvement in this experiment is limited to Dr. Ahmad only.

¹⁵R. Henderson, S. Ahmad *et al.*, IEEE Tran. on Nucl. Science **37**, 1116 (1990).

¹⁶D. Armstrong, Ph. D. Thesis, University of British Columbia, 1988.

D. CEBAF PR-89-024: Radiative Decays of Low-Lying Hyperons

The object of this experiment is to probe the quark wavefunctions of the hyperons by measuring the electromagnetic decays of particular states of the uds quark systems. The experiment will be done at CEBAF which is currently under construction. Specifically, we will measure the branching ratios of the electromagnetic decays of the low lying excited hyperons, $\Lambda(1405)$, $\Lambda(1520)$, and the $\Sigma^0(1385)$, using the CEBAF Large Angle Spectrometer (LAS). We will produce the excited hyperons using a tagged photon beam with $\Delta E_\gamma/E_\gamma = 0.25\%$ FWHM, via the reaction $\gamma p \rightarrow K^+ Y^*$. The Kaon, proton and π^- will be detected in the LAS with both large solid angle and good momentum resolution. The four momentum of the excited hyperon can be reconstructed from the beam photon energy and the kaon momentum; that of the Λ (from the $Y^* \rightarrow \Lambda \gamma$ decays) can be reconstructed from the proton and π^- momentum. Extensive computer modelling of the system indicates that the hyperon mass will be determined to better than 5 MeV FWHM and the Λ mass to better than 2 MeV FWHM. With this mass resolution the backgrounds due to π^0 decays can be efficiently suppressed for the $Y^* \rightarrow \gamma \Lambda$ decays, as is indicated in Figure 8a. Since we also detect the decay photon, the background will be reduced by a large factor. However, due to the limited coverage of the LAS shower counter it will also result in a fourfold decrease in count rate, as is shown in Figure 8b. The $Y^* \rightarrow \gamma \Sigma^0$ decays require the detection of two photons with large solid angle. The current design of the LAS will not have sufficient coverage to accomplish this (see Fig. 9a,b), and this portion of the proposal was deferred.

Unlike other attempts at this measurement, no unknown processes interfere with the interpretation of the results. This feature has particularly excited theorists. The PAC had the following comments on this experiment: "This experiment would provide important information about the quark model wavefunctions of the low-lying Λ and Σ hyperons. This is especially true for the $\Lambda(1405)$ which cannot be directly observed in $K - p$ reactions. Radiative decay measurements can be expected to provide very stringent tests of these models and would help resolve a number of long-standing issues regarding these states."

The proposal for this experiment was submitted to the CEBAF PAC in October 1989, and was approved for 30 days of running - approximately 8% of the beam time that is expected to be available during the first three years. Our proposal was one of the 16 that were approved out of 47 submitted to the first PAC for the new machine. A copy of the proposal is included with the Renewal Proposal.

Figure 8: Missing mass spectrum of photon from reaction $\gamma p \rightarrow K^+ \Lambda(1405), \Sigma(1285) \rightarrow K^+ \gamma \Lambda$

Figure 9: Missing mass spectrum of photon from reaction $\gamma n \rightarrow K^+ \Lambda(1405), \Sigma(1385) \rightarrow K^+ \gamma \Sigma^0$

E. FNAL E683: Photoproduction of Jets in Nuclei

The object of this experiment is to study the influence of the nuclear medium on the creation and subsequent hadronization of jets from the interaction of several hundred GeV photons with both quarks and gluons. The past year has seen the completion of the installation of the apparatus: the upstream and downstream wire chambers, the beam calorimeter, and the muon hodoscope. Beam was first delivered to Wide Band in February of 1990. The experiment upstream of E683 (E687), being prime user, began taking data while we began parasitic studies of both the calorimeters and wire chambers. During this period we balanced the calorimeter phototube high voltages, and made all the wire chambers operational. By May of 1990, both the main calorimeter and beam calorimeter had been checked out, all the phototubes balanced, and the drift chambers calibrated.

During the first week of June 1990, E683 had a one week engineering run, with a second week of test beam in late August of 1990. The goals for these tests were:

1. Establish a beam tune and determine the spot size at the target.
2. Test the triggering and readout of the upstream silicon counters which are part of the beam tagging.
3. Preliminary calibration of both the main calorimeter and the beam calorimeter and rate studies on the beam calorimeter.
4. Preliminary high p_T data.
5. Tests of the effect of E687 material in the beam to examine the feasibility of simultaneous running of the two experiments.

In June, the beam tune was established, and the achieved spot size was as calculated from beam transport programs. However, the same tune was not reproduced in August, for reasons that are not currently understood. During the August run the spot size was much larger and asymmetric, and we had problems with beam scraping as well as a significant halo. Additional instrumentation is being installed to better monitor the beam tune at the E683 target.

Since the Wide Band beam has a momentum spread of $\pm 15\%$, the upstream tagging information, which determines the momentum of the incident beam to 2%, is necessary for calibration as well as high- p_T data. After initial problems were solved, the beam tagging worked well. Figure 10 shows a typical beam energy distribution as measured by the silicon chambers.

The calibration of the newly constructed beam calorimeter (described in the Instrumentation section) demonstrated that it is working as expected. Rate studies indicate that it will withstand expected counting rates, although it is clear that we must monitor nearby beam buckets for pile-up. Calibration data at 30, 60 and 150 GeV, for both pions and electrons was taken at several locations in the main calorimeter. Although the energy resolution is worse than expected, the problem is thought to be due to slight imbalances in phototube response.

In spite of minor problems, we did acquire some high p_T data from Pb and Be targets in June and a larger sample (about 200,000 triggers) in August. Comparison with hadron data from E609 is interesting. The planarity distribution (Figure 11) from photon-induced events is nearly identical to that obtained from a hadron beam. Figure 11 is data taken with a lead target; data from the beryllium target is similar. Figure 12a shows the distribution of energy in the beam calorimeter for photon-induced high p_T events and Figure 12b shows the same distribution for hadron-induced events. The difference here is striking. As expected, little energy goes in the forward direction for photon-induced events compared to hadron-induced events.

We have examined the possibility of simultaneously running E687 and E683, the two experiments which are in the Wide Band beam line. Both experiments would benefit from increased beam time. We conducted tests during our run in June, such as varying the amount of material in the beam upstream of the E683 target, and taking data with the E687 magnets both on and off. Study of these data showed no problems. During our week of test beam in August both experiments ran simultaneously. Based on these results, it seems likely that E687 and E683 will run together during the second half of this fixed-target cycle, currently scheduled to start in December of 1990.

Figure 10: Typical Beam Energy Distribution - Si Chambers

Figure 11: Planarity Distribution from Photon-Induced Events

Figure 12a: Beam cal energy for photon-induced events.

Figure 12b: Beam cal energy for hadron-induced events from E609.

F. Instrumentation Projects

(1) Cylindrical Multiplicity Detector for BNL E854

We are developing a Large Angle Multiplicity Detector (LAMD) system to be used in BNL Experiment E854, described above. This detector is made of 240 ion implanted silicon photodiodes (Figure 13) arranged in 12 pad arrays. Each array (Figure 14) contains 20, 1cm x 1cm silicon diodes with thickness of 500 ± 25 microns. These low noise, fast response diodes along with front end, low noise quad preamplifiers were purchased from Micron Semiconductor Limited, England.

Figure 13: LAMD System

Figure 14: Detail of LAMD 20 Diode Array

The design of the driver amplifier circuit (Figure 15) and the construction of the 210 amplifiers were done at the Bonner Laboratory. These amplifiers will be used to boost the preamp output signals and to drive them over 150 ft ribbon cables to FERA ADC's. The schematic of the electronics from the detector to the FERA ADC's is shown in Figure 16.

Figure 15: Schematic of Pulse Shaping Ampoifier & Line Driver for E854

Figure 16: Block Diagram of LAMD Electronics

We have performed extensive tests with one of the silicon pad arrays. Using the complete electronic set up and triggering on minimum ionizing particles from a ^{100}Ru source, we obtained the typical pulse height spectrum shown in Fig. 17. It appears that the detector will perform as required for determining the multiplicity near 90° in $\bar{p}$ -nucleus annihilations.

Figure 17: LAMD Pulse Height Spectrum for ^{100}Ru Electrons

(2) MWPC Detectors and Electronics for CERN NA47

Several MWPC's are being constructed and instrumented at Rice for the SMC' experiment. The chamber frames and artwork are being fabricated at Rice and the wires will be wound in the Fermilab Lab 6 Shop. We expect to have finished winding the first chamber by November, 1990. We have procured 2208 channels of fully instrumented PCOS III from LeCroy. We have additional amplifier cards donated to us by Professor R. Ruchti of Notre Dame. We have ordered sufficient PCOS III to bring our total to 5280 fully instrumented wires. These will be chamber-mounted over the next few months, and will fully instrument two of the three-coordinate MWPC's to be ready for use by April, 1991. The remaining MWPC's, including the large 1 mm spacing chamber being developed, will be completed for the 1992 run. This effort has involved several students and will constitute M.A. projects for Steve Eichblatt and Greg Morrow.

(3) Lead Glass Array for CERN NA47

The Notre Dame/BNL lead glass wall which we used for BNL E817 has been "donated" to Rice to be rebuilt for the SMC' polarimeter. The lead glass blocks and phototubes were packed and safely transported to Rice. The lead glass and most of the phototubes have been tested and are in excellent condition.

Our design of the lead-glass shower counter calls for the use of 60 blocks of SF5 lead-glass. Each of these has a length of 21.4 cm, with a square face of 10.14 cm x 10.14 cm. The total radiation length of each block is 14.7. We will glue pairs of blocks together to make the total thickness 29.4 radiation lengths. The counters will be stacked in three rows with 10 blocks per row, giving the wall a 30.42 cm x 101.40 cm x 29.40 cm dimension. Thirty PMT's (RCA 4900) will be attached to the back of the lead-glass blocks. A light-tight container and transporter for the rebuilt wall is being designed here at Rice. We expect delivery of all this equipment to CERN early in 1991.

This project will constitute a M.A. project for Hung Cao.

(4) Cylindrical Wire Chamber for LAMPF E1097

Central to LAMPF E1097 is the design and construction of the cylindrical chamber which will surround the target. The chamber will have inner and outer radii of 8 and 30 cm, respectively and a height of 100 cm. The sense wires are arranged in four pairs of cylindrical wire planes. The planes within each pair are offset by half a wire spacing to resolve left-right ambiguities. There are a total of 448 sense wires and 1792 field shaping wires arranged in a hex pattern. The construction of this chamber is being done jointly by us and the University of Texas at Austin (UT).

The chamber will measure positions perpendicular to the wires by measuring the drift time and along the wires using charge division. This requires that the analog signal from both ends of each sense wire be read into ADC's and that some fraction of these signals be

(5) Beam Calorimeter for FNAL E683

The E683 beam calorimeter will serve as a beam flux monitor and measure the forward energy flow for events in which the photon has undergone a hard scatter. This device must have a large dynamic range and also distinguish between electromagnetic and hadronic showers. A beam calorimeter which satisfies these requirements has been built for E683 at Fermilab. It is constructed of 1.5" iron plates interspersed with 1/4" SCSN-61T (Kyowa) scintillators. In addition, there are six 1 cm resolution proportional tube chambers embedded in the calorimeter to give some shower position information.

We tested the calorimeter with beam for two single week periods. The first week was spent mainly verifying photomultiplier balancing, investigating photomultiplier sagging and pile up, and searching for reasonable operating voltages for the PWC's. No sagging was observed, even at the highest intensities studied, and pile up was measured to be as expected.

During the second week of beam we calibrated the response of the calorimeter to electron, pion and gamma beams of various energies. Preliminary results (see Figure 19) yielded worse energy resolutions than anticipated; however, this is now understood. The hadronic energy resolution has been determined to be approximately $(80\%-90\%)/\sqrt{E}$. The design and construction of the beam calorimeter formed the basis for the M.A. thesis of Don Lincoln.

Figure 19: BCAL Response for 60 GeV Pions

(6) Shower Counter for BNL E818

A lead-scintillator sandwich shower counter was designed and built at Rice for use in E818 to veto π^0 production in the LH_2 target. The counter consisted of four quadrants which surrounded the target and cylindrical wire chamber assembly as shown in Figure 20. Each quadrant had five layers of lead sheets followed by 1 cm sheets of NE110 scintillator. The lead sheets are 3, 3, 6, 6 and 6 mm thick respectively. Each of the four lead scintillator stacks were read out from one edge by a 3" x 20" NE174 waveshifter bar. Because the veto counter had to operate in the 0.5T field of the MPS magnet, special high magnetic field resistant phototubes, Hamamatsu R2490, were used. A set of four charged particle veto paddles, 1 cm NE110, were also read out by NE174 waveshifter bars and R2490 phototubes.

Bench tests with a ^{90}Sr electron source showed that for 1 MeV deposited in the shower counter, we obtain a signal corresponding to about 5 photoelectrons. EGS Monte Carlo calculations for the lead-scintillator stack described above indicate a 4 MeV deposition, on the average, for 40 MeV photons and a 50 MeV deposition for 1000 MeV photons. This leads to a signal of 20 to 250 p.e., which is sufficient to reach the design goal of detecting 40 - 1000 MeV photons. Tests made in the 9 GeV/c π^- beam during running of E854 showed that these minimum ionizing particles could be detected with 99% efficiency. The signals from the charged particle veto paddles, however, were only 95% efficient. This can be remedied by new light guides with gentler bends and a larger cross section. Unfortunately, due to delays at the Nuclear Enterprises factory, the scintillator was not delivered in time to use the counter in the winter 1990 E818 run. It is available for future running.

Figure 20: End View of E818 π^0 Veto Counter

(7) Muon Veto Hodoscope for FNAL E683

A muon hodoscope has been constructed for E683, consisting of 32 paddles (15 vertical and 17 horizontal), arranged to shadow the calorimeter — an area of 104" x 80" with a central 8" x 8" hole for the beam. Two scintillator planes provide a rough position measurement in both vertical and horizontal directions. The hodoscope serves two purposes. During the calibration phase of the experiment, it serves as a trigger to indicate that a muon has passed through the apparatus. The muons are then used to study the response of both calorimeters and the wire chambers. The hodoscope also serves as a muon veto during regular data-taking, since muons produce spurious triggers.

During the spring of 1990, E683 used muons to parasitically calibrate and debug its equipment. The muon hodoscope functioned well over a period of several months in this capacity. For the two weeks of test beam in June and August, however, the muon hodoscope was used in veto mode. It was then discovered that the efficiency was not as high as was desirable due to ageing light joints. In addition, the coverage of the veto wall needed to be expanded, and easier access for repair was needed. For these reasons the hodoscope is currently undergoing redesign and reconstruction. The new hodoscope will have a sliding framework for easier maintenance of individual scintillators and phototubes, as well as a larger active area. During the process of reconstruction, all subsystems of the hodoscope are being examined, and, where possible, improved. Included in this process are an examination and reconstruction of all optical joints, as well as a redesign of the phototube bases to improve the quality of the phototube signal. The high voltage control system, high voltage hardware, and downstream logic are also being examined. This project constituted part of the M.A. thesis of Mike Traynor.

4. Changes in Personnel

Research Staff: Dr. Salahuddin Ahmad came from TRIUMF to join the group in January, 1990, as an Assistant Research Scientist, replacing J. W. Kruk. Dr. Stoyan Toshkov came in mid-year to serve as a Visiting Scholar while his wife has a Distinguished Mellon Fellowship in Rice's History Department for the 1990-91 academic year. He most recently worked with Fred Reines at the University of California-Irvine

Graduate Students: New graduate students joining the Medium Energy Group were John Cummings, Steven Eichblatt, and Anton Empl. Rice undergraduates Paul Phillips, Renee Beveridge, and Sharon Casteel spent a busy summer assembling and testing electronics for various experiments. Mike Henry, a 1990 Rice physics graduate, worked in the Lab for the entire spring semester and summer since he had completed his course work in December of 1989.

5. 1990 Publications, Presentations, & Theses

Publications

"Modular TPC's for Relativistic Heavy-Ion Experiments," A. Etkin, B. E. Bonner, G. S. Mutchler *et al.*, Nuclear Instruments and Methods **A283**, 557 (198).

"Analyzing Power of Inclusive Production of π^+ , π^- and K_S^0 by Polarized Protons at 13.3 and 18.5 GeV/c," B. E. Bonner, F. Nessi-Tedaldi *et al.* Physical Review **D41**, 13 (1 January 1990).

"Strangeness Production in Antiproton-Tantalum Interactions at 4 GeV/c," W. R. Gibbs and J. W. Kruk, Physics Letters **B237**, 317 (22 March 1990)

"Neutral V^- Production with 14.6 x A GeV/c Silicon Beams," S. E. Eiseman, B. E. Bonner, G. S. Mutchler *et al.*, submitted to Physics Letters B, May 30, 1990.

Presentations

"Radiative Decays of the Low-Lying Hyperons," G. S. Mutchler, CEBAF, March 19, 1990.

"First Observation of Λ^0 , $\bar{\Lambda}^0$, K_S^0 Production in Relativistic Heavy Ion Collisions at the AGS," *Heavy Ion Physics at the AGS* Brookhaven, March 1990, AIP Conference Proceedings (to be published), T. Hallman, B. E. Bonner, G. S. Mutchler *et al.*

"AGS Silicon Gold Collisions Measured in the E-810 TPC," *Ibid.*, W. A. Love, B. E. Bonner, G. S. Mutchler *et al.*

" V^0 Production with 14.5 GeV/c Silicon Beams," *Ibid.*, A. C. Saulys, B. E. Bonner, G. S. Mutchler *et al.*

"810 Future Plans," *Ibid.*, E. D. Platner, B. E. Bonner, G. S. Mutchler *et al.*

"Partial-Wave Analysis of the $K^+K_s^0\pi^-$ System Produced in π^-p and K^-p Interactions at 8 GeV/c," *MIT PANIC XII*, Boston, June 1990, AIP Conference Proceedings (to be published), S. U. Chung, B. E. Bonner, G. S. Mutchler *et al.*

"Studies of Central Interactions of Si Ions at 14.5 x A GeV/c in Au and Cu," *Ibid.*, K. J. Foley, B. E. Bonner, G. S. Mutchler *et al.*

Ibid., XXVI International Conference on High Energy Physics, Singapore, August 1990, AIP Conference Proceedings (to be published).

"Preliminary Partial-Wave Analysis of the $K^+K_S^0\pi^-$ System Produced in 8 GeV/c K^-p Interactions," *Ibid.*, E. King, B. E. Bonner, G. S. Mutchler *et al.*

Theses

"Spin Effects in Inclusive Strange Particle Production," Nety M. Krishna, Ph.D., Rice University, May 1990.

"Design and Construction of a Beam Calorimeter for E633 at FNAL," Donald W. Lincoln, M.A., Rice University, May 1990.

"Construction of the E683 Hodoscope and Preliminary Calibration of the E683 Main Calorimeter," Michael M. Traynor, M.A., Rice University, May 1990.

"Particle Identification by Time-of-Flight for Heavy Ion Interactions," Cheng-nan Chiu, M.A., Rice University, May 1990.

Principal Investigators

B. E. Bonner, Chairman, Physics Department
& Director, T.W. Bonner Nuclear Laboratories

G. S. Mutchler, Professor of Physics

September 30, 1990

6. COPIES OF SELECTED PUBLICATIONS and MANUSCRIPTS

- E810:** "Modular TPC's for Relativistic Heavy-Ion Experiments," A. Etkin, B. E. Bonner, G. S. Mutchler *et al.*, Nuclear Instruments and Methods **A283**, 557 (1989).
- E817:** "Analyzing Power of Inclusive Production of π^+ , π^- and K_S^0 by Polarized Protons at 13.3 and 18.5 GeV/c," B. E. Bonner, F. Nessi-Tedaldi *et al.* Physical Review **D41**, 13 (1 January 1990).
- E854:** "Strangeness Production in Antiproton-Tantalum Interactions at 4 GeV/c," W. R. Gibbs and J. W. Kruk, Physics Letters **B237**, 317 (22 March 1990)
- E810:** "Neutral V Production with 14.6 x A GeV/c Silicon Beams," S. E. Elseman, B. E. Bonner, G. S. Mutchler *et al.*, submitted to Physics Letters B, May 30, 1990.

MODULAR TPCs FOR RELATIVISTIC HEAVY-ION EXPERIMENTS *

A. ETKIN, S.E. EISEMAN, K.J. FOLEY, R.W. HACKENBURG, R.S. LONGACRE, W.A. LOVE,
T.W. MORRIS, E.D. PLATNER and A.C. SAULYS

Brookhaven National Laboratory, Upton, NY 11973, USA

S.J. LINDENBAUM

Brookhaven National Laboratory and City College of New York, New York, NY 10031, USA

C.S. CHAN and M.A. KRAMER

City College of New York, New York, NY 10031, USA

T.J. HALLMAN and L. MADANSKY

Johns Hopkins University, Baltimore, MD 21218, USA

B.E. BONNER, J.A. BUCHANAN, C.N. CHIOU, J.M. CLEMENT, M.D. CORCORAN, N. KRISHNA,
J.W. KRUK, H.E. MIETTINEN, G.S. MUTCHLER, F. NESSI-TEDALDI, M. NESSI, G.C. PHILLIPS
and J.B. ROBERTS

Rice University, Houston, TX 77251, USA

A description is given of a TPC system that operates in a relativistic heavy-ion beam and yields good track reconstruction efficiency in very-high-multiplicity events. The mechanical construction of the chamber is discussed. A set of custom hybrid circuits are used to build a very compact, cost-effective electronics system mounted directly on the chamber. Results from running in test beams and from preliminary experimental runs are given.

1. Introduction

A TPC (time projection chamber) system has been built for BNL experiment 810, which is a study of particle production in relativistic heavy-ion collisions. The events of interest have very high multiplicity (> 100 tracks). TPCs were chosen as the tracking detectors because they measure true three-dimensional points along the tracks, a very significant advantage for track reconstruction.

In order to have good event reconstruction in these high-multiplicity events it is important to optimize the two-track resolution by having a large number of independent readout elements. We have used rows of short (~ 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. Use of the short anode wires precludes using dE/dx for particle identification, which in the kinematic region of interest and at the particle densities in these events is a very expensive and extremely difficult task.

The TPC system consists of three separate modules which improve the system reliability. Readout electronics uses custom hybrids to produce a very compact, cost-effective system. In order to maximize the acceptance the ion beam is incident on the middle of the chamber, which limits the maximum useful ion beam.

2. TPC modules

The front view of a module is shown in fig. 1. In the vertical drift region (60 cm high $\times$ 65 cm wide $\times$ 47 cm long) a field cage with double-sided printed circuit boards on the sides and a double row of wire electrodes at each end shapes the electric field. The readout is

* This research was supported by the US Department of Energy under Contract Nos. DE-AC02-76CH00016, DE-AC02-83ER40107, DE-AS05-81ER40032 and DE-AC02-76ER03274, and the City University of New York PSC-BHE Research Award Program.

Fig. 3. View of the main electrical connections to modules.

achieved by 36 rows (12 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 unambiguous 3D points along the tracks. Fig. 2 shows the three modules located in the center of the MPS magnet (looking downstream) and fig. 3 is a closeup of the connections to the module. Electrons produced by charged particles in the drift region must pass through a gating grid and a wire cathode in order to reach the anodes. A second, solid copper, cathode below the anodes helps to achieve high gain. The arrangement is shown in fig. 4. In TPCs the

maximum beam rate is limited by field distortion due to positive ion buildup in the drift region. A major source of positive ions are ions produced in the gas amplification process at the readout anodes that leak into the drift volume. A gating grid is used to prevent the transfer of drifting electrons from the drift region to the detector region and that of positive ions in the reverse direction except for selected events. Gating is achieved by applying different potentials to adjacent wires as indicated in fig. 4, collecting the electrons on the more positive wires. When the trigger system indicates that an event of interest has occurred the gate wires are shorted together for 30 ns, a little longer than the maximum drift time, allowing ionization from the tracks to reach the amplification region. Because of their slower drift velocity, positive ions from amplification at the anode do not reach the gating grid before the gate is closed, further improving the gating of the TPC.

Fig. 4. Schematic of the arrangement of the electrodes in the detector end cap.

3. Electronics

Since dE/dx is not measured in this system the electronics is only required to give time information. In order to read out the many closely spaced short anodes at minimum cost, a circuit was designed that allows each individual channel to be mounted directly on the chamber and to occupy only the anode wire spacing. The circuit for each channel is shown in fig. 5. Sixteen channels are assembled in a hybrid package* with

* TeCrov HTD 161S.M

the TPC modules perpendicular to the wire rows and perpendicular to the magnetic field. The incident beam particles were tracked through two MPS multiplane PWC modules (run at reduced voltage for the Si beam,

since the ionization of the ions is 196 times that of the hadron beams usually used) and a thin plastic Cerenkov counter for silicon identification. The measured beam tracks were used to calibrate the TPC with the magnet

Fig. 9. Computer reconstruction of event 301 which has 102 tracks from a primary vertex: (a) $x-z$ view, (b) $y-z$ view, (c) $x-y$ view, (d) rotated view.

Fig. 9 (continued).

off (alignment runs). A few hundred tracks can align the TPC to 100 μm and measure the drift velocity to better than 1%. The TPC modules were operated at about 330 V/cm with a drift velocity of 2.3×10^6 cm/s. The MPS magnet was run at 5.0 kG.

Using the proton beam, the efficiency for minimum ionizing particles was measured to be $> 97\%$ for several

rows (the other rows had electronic problems that have been fixed). The rms position resolution, as measured by fitting proton beam tracks, was 0.6 mm (x = wire direction) and 0.5 mm (y = drift direction), and by fitting Si beam tracks it was 0.6 mm in x and 0.25 mm in y . Using secondary tracks from Si interactions the rms deviations from fits were 0.9 mm in x and 0.75 mm

in y (note these results include all fitted tracks including pattern recognition mistakes).

Fig. 7 ($1/p$ for beam tracks reconstructed in the

TPC) shows the momentum resolution of the test setup. The sigma for the $1/p$ plot gives directly the dp/p^2 resolution. Shown is the resolution measured using a

Fig. 10. Computer reconstruction of event 8789 which has 77 tracks from a primary vertex: (a) $x-z$ view, (b) $y-z$ view, (c) $x-y$ view, (d) rotated view.

Fig. 10 (continued).

silicon beam with $2\frac{1}{2}$ modules (31 rows). The curve is a Gaussian approximation to the measurements and not a fit. The sagitta error that corresponds to the σ of the Gaussian is 0.32 mm.

Targets of gold (0.025 mm thick), tin (0.1 mm thick), copper (0.15 mm thick), aluminum (0.8 mm thick) and

carbon (1.5 mm thick) were used. Interactions were selected by using a veto counter located behind the MPS. A discriminator was set to veto events which had a signal greater than half the silicon beam pulse height in the veto counter. The raw beam rate in the chamber was about 1000–2000 ions per pulse. The veto counter

Fig. 11. Expanded view $x-z$ of only the tracks from the Λ candidate in event 8789.

pulse height was encoded with an ADC and recorded with the data so that software cuts could eliminate all events with pulse heights as large as that expected from an alpha surviving from the silicon projectile. This total disintegration of the projectile was defined as our "central" trigger.

Events representing silicon "central" collision were selected by applying two software cuts to the reconstructed events. The cuts were the following:

(1) A vertex is located between $z = 60$ and $z = 66$ in the MPS coordinate system. z is the beam direction axis and the target was located at $z = 63$. The next plot (fig. 8) is a z -distribution of some of the reconstructed vertices from the gold target with a looser veto counter cut.

(2) Veto counter corresponding to no more than two minimum ionizing tracks.

Figs. 9a-d show the computer reconstruction of four views of a silicon-gold event (number 301) with 102 tracks (out of a total of 130 tracks found) from primary vertex ($z = 63.2$). If we examine similar events in more detail we can see that the pattern recognition algorithm is not yet perfect, although it is good enough that one can sometimes spend a long time deciding what should have been done with hits that are not assigned to tracks.

Different views of event 8789 are shown in figs. 10a-d. This event has 77 tracks associated with a vertex ($z = 63.5$) at the target. In addition to the primary vertex there is a secondary vertex which is consistent

with being a Λ decay vertex; Fig. 11 shows an expanded projection of the tracks assigned to the decay vertex. *

In a previous run using an oxygen beam and prototype TPCs we studied beam rate limitations in the TPC. In a high-intensity run some qualitative measure of the effects of space charge buildup (with time) due to primary ionization only was obtained. Beam intensity varied from 2×10^4 to 10^5 oxygen ions per (one second) AGS beam spill. The highest intensity produces track distortions corresponding to more than 2 mm sagitta (in the $y-z$ plane) and a substantial loss of efficiency in some rows. The average sagitta at 2×10^4 oxygen ions was 0.55 mm. This latter intensity corresponds to 5000 sulfur ions or to 1.2 million minimum ionizing particles (hadrons) per second.

The density of tracks from oxygen and silicon events offer many opportunities to study the two-track resolution of the device. There are cases where the device produces apparently separate signals for tracks as close as 2.5 mm. However, a feature of the pattern recognition algorithm is that it merges hits on adjacent wires if the signals in the drift direction overlap. This means for practical purposes that two tracks are properly sep-

* From a very preliminary analysis of a small sample, the signal and background-to-background ratio is $\sim 2.5:1$ for the lambda peak.

arated 50% of the time by the pattern recognition if they lie inside the same $5\text{ mm} \times 5\text{ mm}$ area in the x - y projection.

5. Conclusion

We have developed a TPC system for use in relativistic heavy-ion experiments that permits the efficient re-

construction of high-multiplicity events including events with decay vertices. It operates with the beam through the middle of the chamber giving good efficiency, two-track separation and spatial resolution. The three-dimensional points in this system allow the reconstruction of the complex events of interest. The use of specially developed hybrid electronics allows us to build a compact and cost-effective system.

Analyzing power of inclusive production of π^+ , π^- , and K_S^0 by polarized protons at 13.3 and 18.5 GeV/c

B. E. Bonner, J. A. Buchanan, J. M. Clement, M. D. Corcoran, N. M. Krishna, J. W. Kruk, H. E. Miettinen, R. M. Moss, G. S. Mutchler, F. Nessi-Tedaldi, M. Nessi, G. C. Phillips, J. B. Roberts, P. M. Stevenson, and S. R. Tonse
T. W. Bonner Laboratories, Physics Department, Rice University, Houston, Texas 77251

A. Birman, S. U. Chung, A. Etkin, R. C. Fernow, H. Kirk, S. D. Protopopescu, and H. Willutzki
Physics Department, Brookhaven National Laboratory, Upton, New York 11973

T. Hallman and L. Madansky
Department of Physics and Astronomy, Johns Hopkins University, Baltimore, Maryland 21218

Z. Bar-Yam, J. Dowd, W. Kern, and E. King
Department of Physics, Southeastern Massachusetts University, North Dartmouth, Massachusetts 02747

B. W. Mayes and L. S. Pinsky
Physics Department, University of Houston, Houston, Texas 77004
 (Received 3 August 1989)

We have measured the analyzing power in π^+ , π^- , and K_S^0 production by a polarized proton beam at 13.3 and 18.5 GeV/c. The data cover the central and the beam fragmentation region, in the transverse-momentum range up to 2 GeV/c. The results indicate that sizable effects are present at high x_F and also persist into the hard-scattering region for K_S^0 and π^+ . A zero value of the analyzing power was observed for π^- production.

In recent years, measurements of single-spin-dependent observables in the production or scattering of hadrons have been acquiring an increasing interest due to the implications they have for our knowledge of QCD. In particular, the production of mesons or jets at high transverse momenta p_T has been the object of several theoretical investigations, since unexpected nonvanishing spin effects have been observed in inclusive meson production off a polarized target.^{1,2} The measured quantity is the spin-dependent asymmetry of the production cross section or analyzing power A , which is defined as

$$A = \frac{1}{P_B \cos \phi} \frac{N_+(\phi) - N_-(\phi)}{N_+(\phi) + N_-(\phi)}, \quad (1)$$

where N_+ (N_-) is the number of mesons produced for beam spin up (down), normalized to the beam flux, and ϕ is the mean angle between the beam polarization direction and the normal to the meson production plane. P_B is the average beam polarization. According to this definition, the analyzing power is positive when more particles are produced to the *left* for beam polarization up.

In the central region the argument against seeing such effects is based on an underlying asymmetry at the quark level³

$$A(q_1 q \rightarrow qx) = \alpha_s \frac{m_q}{\sqrt{s}} f(\theta) \quad (2)$$

that leads to almost vanishing values, being proportional to the constituent-quark mass m_q divided by the available center-of-mass energy $\sqrt{s}$. This, however, represents only one of the possible higher-twist processes that can contribute.⁴ For example, a recent calculation by Sivers⁵ provides a new approach within QCD hard scattering that can lead to single-spin production asymmetries. The mechanism involved is a "trigger-bias" effect that arises if one takes into account the orbital motion of the constituents in a polarized proton. In this case, analyzing power values of a few percent can be expected up to transverse momenta of 10 GeV/c. This mechanism is based on an asymmetry in the parton x, k_T distributions and does not require an asymmetry in the parton-parton hard-scattering cross section.

At the other end, in the soft-scattering region, a simple phenomenological approach based on spin-orbit coupling in the fragmentation and recombination of valence and sea quarks provides a satisfactory description of the observed pattern of spin effects in meson and hyperon production.⁶⁻⁸ These models, however, give no quantitative estimate of the quark polarization. An extensive study of production processes of different mesons over an extended kinematic region is clearly necessary to better understand these phenomena.

We present here the results of analyzing power measurements performed in inclusive charged-pion and K_S^0 production with a polarized proton beam incident on a

beryllium target (polyethylene for part of the pion data) at beam energies of 13.3 and 18.5 GeV/c at the Brookhaven Alternating Gradient Synchrotron (AGS). The data were taken during two different AGS polarized-beam runs separated by about two years. About $36 \times 10^4 \pi^-$ and $4 \times 10^5 \pi^-$ were collected in the first run, and $102 \times 10^3 \pi^-$ represent the combined samples of both runs. The kaon data from the first run have been published in Ref. 8. The average value of the vertical beam polarization component was 0.63 (0.36) at 13.3 (18.5) GeV/c in the first run, and 0.44 during the second one, for a beam momentum of 18.5 GeV/c. The setup used for the measurements is extensively described in Ref. 8, along with the beam characteristics and the event reconstruction methods. Briefly, charged-track reconstruction was provided by the Brookhaven multiparticle spectrometer⁹ and pions were identified by a gas threshold Čerenkov counter and companion hodoscope segmented into matching modules. For the 13.3 GeV/c running where the pions were taken parasitically to the Λ triggers, the Čerenkov counter was set to a threshold selecting pion momenta above 2.1 GeV/c. For the 13.3-GeV/c runs dedicated to the pion triggers, the threshold was raised to 3.0 GeV/c. For the 18.5-GeV/c run, the pion momentum threshold was 3.2 GeV/c.

Kaons were identified through the reconstruction of an effective mass calculated under the $K_S^0 \rightarrow \pi^+ \pi^-$ hypothesis. No pion identification was used, in order to avoid biases in kinematic acceptance. The mass peak has a resolution σ of 7 MeV/c². The background underneath the peak accounts for 3.7% of the events, and it is mainly due to poorly reconstructed kaons and Λ 's.

Whereas in Ref. 8 we studied and presented polarization effects in the production of hyperons in the beam fragmentation region, these data for meson production also cover the central region and transverse momenta up to 2 GeV/c. To allow a better comparison between different incident momenta, we will present our data as a function of x_F (Feynman x) and $x_T = 2p_T/\sqrt{s}$. Hence, the c.m.-system production angle between produced par-

FIG. 2. A results for π^- and π^+ production as a function of x_T .

ticle direction and beam direction is uniquely defined by x_F and x_T .

The results for pion production are shown in Fig. 1 as a function of x_F , and in Fig. 2 as a function of x_T . We observe no energy dependence. The analyzing power for π^- production are consistent with zero over the whole kinematic range, with a possible negative trend for values of x_F larger than 0.4. For π^+ production, A rises with x_F , with an average value of about 0.05.

For kaon production we have plotted the results as a function of x_F in Fig. 3 and as a function of x_T in Fig. 4. We observe increasingly negative values for positive x_F , whereas in the central and target-fragmentation region the analyzing power shows rather constant values, around -0.08 . Examining the data as a function of x_T for different bins of x_F , we find that the measured values are the superposition of a constant effect present throughout the kinematic range, and another "component" whose magnitude increases with x_T and is only present in the beam fragmentation region. In the same kinematic region, our measurements of A in Λ and Σ^0 production⁸ gave values consistent with zero.

FIG. 1. Analyzing power A results for π^- and π^+ production as a function of Feynman x .

FIG. 3. Analyzing power results for K_S^0 as a function of Feynman x for the two beam energies.

FIG. 4. A results for K_S^0 produced with a 18.5-GeV/c beam as a function of x_T and for different bins of x_F .

As mentioned, hints of a nonvanishing analyzing power in the central region have already been seen in a few other experiments. In $p + p \rightarrow \pi^0 + X$ at 24 GeV/c using a polarized target¹ at the CERN Proton Synchrotron a similar transverse-momentum range was covered at small x_F . The value of A reaches about 0.5 for $p_T \sim 2$ GeV/c (to be compared to our data, the sign for A measured off polarized targets at $x_F \approx 0$ as published has to be reversed). A measurement of π^0 production with $x_F < 0.1$ performed at Serpukhov with a 40-GeV/c π^- beam on a polarized proton target gave A of the order 0.3 in a similar p_T range.²

Preliminary results for the central region taken at the Brookhaven AGS (Ref. 10) show values consistent with zero for the analyzing power in π^- production over the whole kinematic range. For π^+ production, the effects are positive. Values around 0.07–0.10 are observed for $x_F \approx 0.6$ in the central region, rising to about 0.3 for $x_F \approx 0.8$.

Also some soft-scattering data are available for comparison. Charged-pion and kaon production has been measured using an 11.75-GeV/c polarized proton beam at the Argonne Zero Gradient Synchrotron.¹¹ The π^+ data show a strong x_F dependence. A rises from slightly negative values at low x_T and x_F to values around 0.4 for $x_F \geq 0.8$. The high- x_F results for π^- production show a considerable structure, but are consistent with becoming zero for transverse momenta higher than 0.7 GeV/c.

Examining our data together with all the results above we observe a statistically good agreement in the region of overlap. Broadly speaking the pion data are characterized as follows: the analyzing power for π^- production is always positive whereas for π^+ it vanishes in the central region. In π^+ production a strong x_T dependence is present in the central region, whereas A seems to depend on x_F in forward production.

The behavior of the K_S^0 data is very different: no x_T dependence is observed in the central region, whereas in forward production it is clearly present. These data show a nonzero analyzing power that persists throughout the central region down into the fragmentation region of the unpolarized target.

A satisfactory interpretation of all these results is still unavailable. For the beam fragmentation region, inaccessible heretofore to perturbative QCD calculations, a phenomenological model in terms of parton fragmentation and recombination along with a trigger-bias effect⁶ first used to explain polarization in Λ production successfully reproduces the observed regularities in π^+ , π^- , and K_S^0 production at high Feynman- x values.¹² This is not the case for the π^- data, however, which still leaves an open question. This model cannot be extended into the central region because there the dynamics of the production cannot be described in terms of the recombination of fast beam fragments having spin correlated to that of the incident particle.¹³ It is difficult to imagine that a spin transfer could occur from the polarized beam to the backwards produced kaons. Therefore, an explanation of the present kaon data in these terms is impossible.

However, the central-region data cover a kinematic range where perturbative methods may begin to be applicable. For a long time, the existence of a nonzero analyzing power was considered improbable by most theorists.³ As mentioned earlier, other mechanisms have recently been investigated⁵ that can produce nonvanishing effects. Here the same magnitude and sign are expected for the analyzing power in the production of the different mesons. In this model the analyzing power arises from the orbital motion of the quarks coupled to the spin and thus the sign is independent of the quark mass. While the central region π^+ and π^- results^{1,2} are in agreement with this expectation, the difference in sign between the analyzing power of pions and that of K_S^0 's in our data contradicts this expectation. The sign difference for A between K_S^0 's and pions might indicate that the strange sea quarks in the proton are polarized with opposite transversity to the nonstrange ones.

The interpretation of all these results is also affected by the controversial question of just where hard scattering begins, since many believe that larger values of transverse momentum are required than reached in measurements to date. Higher-energy measurements, such as those upcoming in Fermilab Experiment E704 at 200 GeV/c beam momentum, will certainly provide clues which might better our understanding of these phenomena.

This experiment was supported by the U.S. Department of Energy. We are grateful to the entire staffs at the Alternating Gradient Synchrotron Department, the Multiparticle Spectrometer group, and the Brookhaven National Laboratory Applied Mathematics Department.

¹J. Antille *et al.*, Phys. Lett. **94B**, 523 (1980).

²V. D. Apokin *et al.*, in *High Energy Spin Physics*, proceedings of the 7th International Symposium, Protvino, USSR, 1986 (Institute of High Energy Physics, Protvino, 1987), p. 83.

³G. L. Kane *et al.*, Phys. Rev. Lett. **41**, 1689 (1978).

⁴N. Craigie, K. Hidaka, M. Jacob, and F. M. Renard, Phys. Rep. **99**, 69 (1983).

⁵D. Sivers, Phys. Rev. D **40**, 83 (1989).

- ⁶T. A. DeGrand and H. I. Miettinen, *Phys. Rev. D* **23**, 1227 (1981); **24**, 2419 (1981); T. A. DeGrand, J. Markkanen, and H. I. Miettinen, *ibid.* **32**, 2445 (1985).
- ⁷B. E. Bonner *et al.*, *Phys. Rev. Lett.* **61**, 1918 (1988).
- ⁸B. E. Bonner *et al.*, *Phys. Rev. Lett.* **58**, 447 (1987); *Phys. Rev. D* **38**, 729 (1988); M. Nessi, *Proceedings of the 8th International Symposium on High Energy Spin Physics*, Minneapolis, Minnesota, 1988, edited by K. Heller (AIP Conf. Proc. No. 187) (AIP, New York, 1989), p. 66.
- ⁹S. Eiseman *et al.*, *Nucl. Instrum. Methods Phys. Res.* **217**, 140 (1983).
- ¹⁰D. Barton *et al.*, in *Future Polarization Physics at Fermilab*, proceedings of the Symposium, Batavia, Illinois, 1988, edited by E. Berger, J. Morfin, A. Read, and A. Yokosawa (Fermilab, Batavia, 1988).
- ¹¹W. H. Dragoset *et al.*, *Phys. Rev. D* **18**, 3939 (1978).
- ¹²B. E. Bonner *et al.*, *Phys. Rev. Lett.* **62**, 1591 (1989).
- ¹³J. R. Johnson *et al.*, *Phys. Rev. D* **17**, 1292 (1978); G. R. Farrar *et al.*, *Phys. Lett.* **69B**, 112 (1977); H. E. Fisk and F. Sciulli, *Annu. Rev. Nucl. Part. Sci.* **32**, 499 (1982).

STRANGENESS PRODUCTION IN ANTIPROTON-TANTALUM INTERACTIONS AT 4 GeV/c

A. R. GIBBS

Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA

and

J. W. KRUCK

F.W. Bonner Nuclear Laboratory, Physics Department, Rice University, Houston, TX 77251, USA

Received 15 September 1989; revised manuscript received 13 December 1989

A general measure of strangeness production in antiproton-nucleus interactions is given which is unaffected by strangeness exchange reactions occurring after the initial annihilation. An intranuclear cascade model of p-nucleus interactions has also been developed. Both approaches are applied to data on strange particle yields and rapidity distributions obtained in 4 GeV/c $\bar{p}$ -Ta collisions. No evidence is seen for exotic phenomena.

1. Introduction

Central annihilations of energetic antiprotons in nuclei create a high temperature [1] and a high energy density [2], over a small volume, suitable for the investigation of the possible phase transition to a quark-gluon plasma. The principal questions addressed in the planning and analysis of such experiments are:

- (a) What energy densities have actually been achieved?
- (b) Has such a phase transition taken place?

For the first question it is a matter of developing measures in the classical hadronic representation of the nuclear conditions in terms of spectra of pions, nucleons and other particles emitted. For this purpose the use of modeling techniques, such as the intranuclear cascade code to be described below, are valuable. However in this paper we treat only one aspect of the second question, which is the use of the production of strangeness as an indication of the occurrence of a phase transition.

Strangeness production is normally forbidden so that only a few percent of strange and antistrange quarks are produced in hadronic reactions. As discussed by Rafelski [1], in a quark-gluon plasma all quarks will be on the same footing, so the number of strange quarks would be equal to the number of light (up and down) quarks. The fraction of strange quarks obtained in this manner is considerably larger than that found in ordinary hadronic reactions. He also pointed out that the large number of non-strange mesons present in a hot (color singlet) soup will produce an appreciable amount of strangeness by means of reactions such as $\pi^- p \rightarrow K^0 \Lambda$. This component of strangeness production must be understood and subtracted from any signal observed before drawing any conclusions about the occurrence of a phase transition.

Before entering into the details of how this component can be estimated, we need to discuss the measurement of the strangeness signal itself. The normal convenient experimental variables are abundances of the short-lived kaons (K_S), the Λ 's, and the $\bar{\Lambda}$'s. While the measurement of a Λ gives evidence of the presence of a strange quark and that of an $\bar{\Lambda}$ an anti-strange quark, the observation of a K_S only shows that

¹ Present address: Center for Astrophysical Sciences, Johns Hopkins University, Baltimore, MD 21218, USA.

there was either a strange or an antistrange quark present. We note that once the strange-antistrange pair is produced in the nucleus the strange quarks can be transferred more or less freely between hadrons. For example: $\bar{\Lambda}$'s will most likely annihilate in the nuclear medium (leaving their antistrange quark in a K^+ or K^0 meson), while $\bar{K}$ mesons have a very strong interaction with nucleons and tend to convert with high probability to Λ 's by the $\bar{K}N \rightarrow \pi\Lambda$ reaction. Thus the observation of a single type of strange particle can be very misleading.

Because of the ambiguity of the K_S detection we do not have a direct measure of the strange (or antistrange) quarks contained in mesons. However, if we use the additional constraint that the number of strange quarks is equal to the number of antistrange quarks, we can get a measure of the strangeness produced by simply adding the number of strange and antistrange quarks and dividing by two. The number of hyperons plus the number of antihyperons gives us the part of this sum contained in the baryonic sector. For the K_S we must take into account that they signal the existence of *either* a strange or an antistrange quark. In addition, we must also include unobserved events inferred from these observed particles. First of all, the K_S 's represent only one half of the neutral kaons produced, the other half being long lived and hence not observed in the experiment. In most experiments the charged kaons are not identified. If this is the case then we expect, by isospin symmetry, that there are as many charged as neutral kaons. (We neglect the small correction due to the possibility that the nucleus may not have an equal number of neutrons and protons.) Thus included in the measure of the total number of strange plus antistrange quarks should be a factor of 4 times the number of K_S 's observed. Thus the total number of strange-antistrange quark pairs produced in a reaction is

$$S = (4N_K + N_Y + N_{\bar{Y}}) / 2, \quad (1)$$

where N_K is the number of K_S 's, N_Y is the number of hyperons, and $N_{\bar{Y}}$ is the number of antihyperons observed in each case per annihilation. When computing p -nucleus interactions with p -nucleon interactions in free space we have chosen to consider the strangeness production per annihilation rather than strangeness production per cross section. Strangeness production cross sections are difficult to interpret in a model independent way because p interactions with nuclei are frequently multistep processes; annihilations, however, can occur only once. For a signal of the phase transition one could plot S as a function of temperature or energy density, or even simply energy deposition, to look for an abrupt increase at some given critical value.

Let us take as an example the experiment of Miyano et al. [3] in which rapidity distributions and cross sections for the production of K_S 's, Λ 's and $\bar{\Lambda}$'s were measured in p -Ta collisions at an incident momentum of 4 GeV/c. This experiment comes the closest to providing the conditions necessary to produce the putative phase transition in a p -nucleus collision [2,4]. This experiment observed a large enhancement in the number of Λ 's, a large decrease in the number of $\bar{\Lambda}$'s, and a sizeable decrease in the number of K_S 's, relative to p -nucleus annihilations in free space. The observed cross sections were:

$$\sigma(\text{total inelastic}) = 1628.0 \pm 30.0 \text{ mb},$$

$$\sigma(\Lambda) = 193.0 \pm 12.0 \text{ mb},$$

$$\sigma(K_S) = 82.0 \pm 6.0 \text{ mb},$$

$$\sigma(\bar{\Lambda}) = 3.8 \pm 2.0 \text{ mb}.$$

Calculation of the strangeness production S for the experiment of Miyano et al. requires knowledge of the total annihilation cross section. Using an INC code (described below) to study this reaction, we find that 92% of all inelastic events resulted in an annihilation, so we estimate the annihilation cross section to be 1498 mb. The resulting experimental value for S is

$$S = (4 \times 0.055 + 0.129 + 0.003) / 2 = 0.176. \quad (2)$$

The INC code indicates that associated production reactions occurring during the cascade contribute about 0.018 to S ; the effective value of S is thus

$$S = 0.158. \quad (3)$$

Computing the amount of strangeness S in the spectra at 4 GeV/c gives $S = 0.158$ for the p -nucleus collision and $S = 0.176$ for p -p.

$$S = (4 \times 0.076 + 0.021 + 0.021) / 2 = 0.176. \quad (4)$$

These values are in excellent agreement with the value obtained from the K_S data of Miyano et al.

15. Obviously, anything the experiment observed as strangeness is an expected

2. Computational technique

In order to better understand the process involved in p-nucleus collisions we have written an intra-nuclear cascade code, whose basic features are as follows. The nuclear target is modelled by a system of A nucleons propagating in a 50 MeV Saxon-Woods potential with classical motion. A pair of nucleons will scatter elastically (with an isotropic angular distribution in the CM) if separated by less than the distance corresponding to a classical circular cross section of 40 mb. Λ 's and Σ 's produced in the nucleus are treated similarly, except that they propagate in a 30 MeV potential well [14] and are assigned an elastic scattering cross section of 14.4 mb. The results of the calculation presented here are not generally very sensitive to the uncertainties in the cross sections for the processes implemented in the code. A major exception is the Λ -nucleon total cross section, which is poorly known in the energy region of interest. It appears to be about a factor of two smaller than the nucleon-nucleon cross section at these energies; if it were simply set equal to the nucleon-nucleon cross section (which is the case at high energies), the net effect would be roughly to shift the Λ rapidity distribution toward lower values by 0.08 units of rapidity.

Incoming antiprotons may interact through the channels

- $pN \rightarrow \bar{p}N$,
- $pN \rightarrow \bar{p}N\pi$,
- $pN \rightarrow \bar{\Lambda}\Lambda$,
- $pN \rightarrow \bar{\Lambda}KN$,
- $pN \rightarrow \bar{N}AK$,
- $pN \rightarrow \pi's$,
- $pN \rightarrow K\bar{K}\pi's$.

The cross sections for each channel and the angular distributions are taken from refs. [5-13]. The cross section for the $pN\pi$ channel was scaled to match the total inelastic non-annihilation cross section; the Λ

production channels were similarly increased to match the total inclusive Λ cross section. If a Λ is produced it may undergo the following interactions:

- $\Lambda N \rightarrow \Lambda N$,
- $\Lambda N \rightarrow \Lambda N\pi$,
- $\Lambda N \rightarrow K\pi's$,
- $\Lambda N \rightarrow K\bar{K}K\pi's$.

The cross sections and angular distributions used are the same as for the corresponding p channels.

Mesons produced in annihilations are propagated within the nucleus with no central potential (in contrast to the case for the baryons) but with the following reactions occurring:

- $\pi N \rightarrow \pi N$, $\pi N \rightarrow \omega N$, $K N \rightarrow \bar{K} N$,
- $\pi N \rightarrow \pi N^*$, $\pi N \rightarrow K\Lambda$, $K N \rightarrow \pi\Lambda$,
- $\pi N \rightarrow \pi\Delta$, $\pi N \rightarrow K\Sigma$, $K N \rightarrow \pi\Sigma$,
- $\pi N \rightarrow \pi\pi\pi N$, $\pi N \rightarrow K^*\Lambda$, $K N \rightarrow K N$,
- $\pi N \rightarrow \omega N$, $\pi N \rightarrow K^*\Sigma$,
- $\pi N \rightarrow \eta N$.

The pion induced reactions are very important since these deposit most of the energy and produce strangeness as well. Their calculation is implemented by first deciding if there is to be a pion-nucleon collision based on each pion-nucleon distance compared to the pion-nucleon total cross section in the laboratory. The momentum used for the cross section is the effective momentum that the pion-nucleon system would have if the nucleon were at rest, i.e., the Fermi motion of the nucleon is taken into account as if it were on shell. Once it is determined that a pion-nucleon collision will take place a number of branches are possible. These are chosen according to the cumulative probabilities given in fig. 1. The logarithmic graph is used so that the small, OZI forbidden, particle productions can be seen. The $\pi-2\pi$ and $\pi-3\pi$ reactions are important for an estimate of energy deposition. They also limit the contribution of associated production reactions by reducing the pion energy to below threshold for strangeness production. These probabilities were calculated from data taken from the CERN-HERA [15] reports.

Fig. 1. Cumulative probabilities for πN channels as a function of relative momentum.

The kaon reactions are treated in a similar, but less exhaustive manner.

3. Strangeness production

As mentioned earlier, an enhancement in strangeness production has been suggested as a signal of the formation of a quark-gluon plasma. By running the classical nuclear modeling code we have just described we obtain results for the various strangeness channels in good agreement with those seen by Miyano et al. and in agreement with the simple formula derived at the beginning of the paper. This last is expected of course since the formula is general. The real question to be answered by the code is "how much strangeness is produced in the pion-nucleon reactions?" This is the amount by which nuclear production of S should exceed the p-p production. Table 1 shows the strangeness balance from intranuclear reactions. The sums over all channels are in reasonable agreement with experiment. The pion-induced reactions are seen to produce roughly 14% of the Λ 's and 7% of the K 's. Since the experiment did not distinguish Σ 's from Λ 's, we have counted 1/3 of the Σ 's pro-

Table 1
Frequency of occurrence of various channels, expressed as a percentage of the annihilation rate

	Λ (%)	K_S (%)	Σ (%)
$pN \rightarrow \Lambda\Lambda$	0.99	0.90	0.99
$pN \rightarrow \Lambda KN$	0.52	0.13	0.90
$pN \rightarrow \Lambda KN$	0.00	0.14	0.55
$pN \rightarrow KK\pi$'s	0.00	0.02	0.00
$\Lambda N \rightarrow K(KK)\pi$'s	0.00	0.13	1.07
$KN \rightarrow \pi\Lambda, \pi\Sigma$	8.48	2.70	0.00
$\pi N \rightarrow K\Lambda$ or $K\Sigma$	1.57	0.51	0.00
sum	11.56	5.43	0.47
experiment	12.88 ± 0.80	5.47 ± 0.40	0.28 ± 0.13

duced as Λ 's. The inclusive cross sections predicted by the code are

$$\sigma(\Lambda) = 19.5 \text{ mb},$$

$$\sigma(K) = 9.2 \text{ mb},$$

$$\sigma(K_S) = 10.2 \text{ mb}.$$

The code has also been used to calculate rapidity distributions. The Λ distribution is shown in fig. 2.

Fig. 2 Rapidity distribution of Λ 's produced in 4 GeV/c p-Pa interactions. Solid circles are data of Miyano et al. Open squares are results of the INC calculation.

Fig. 3 Rapidity distribution of K_S 's produced in 4 GeV/c p-Pa interactions. Solid circles are data of Miyano et al. Open squares are results of the INC calculation.

and the K_S distribution is shown in fig. 3. Both distributions are in excellent agreement with the data. Thus it seems that no exotic effects are needed to explain the data [16].

There is one potential ambiguity to be considered when comparing model calculations with this data, which concerns the treatment of Λ 's that are produced but remain bound in the nucleus. The INC code

indicates that about 11% of the produced Λ 's had remain bound in this experiment. Such particles are not observed experimentally, and would not ordinarily be included in a cross section. The ambiguity arises from the corrections needed in this experiment to account for particles observed in the thick target foils; if it includes an extrapolation down to zero Λ momentum it may effectively include bound Λ 's. We have not included bound Λ 's in any of our INC results.

We wish to point out two other references [17,18] which use different techniques than the present work and a third [19] which also uses an INC approach. In the last case a significant amount of associated production is predicted, apparently in contradiction with the present work and with the data.

4. Conclusions

Analysis of the strangeness produced in the recent p-nucleus experiment by Miyano et al. shows it to be completely consistent with no enhanced strangeness production both from the detailed model calculation and from general strangeness conservation considerations. The rapidity distributions calculated by this model are in excellent agreement with the data as well even though they are sensitive to more detailed assumptions of the model.

Acknowledgement

This work was supported in part by the US Department of Energy (DE-FC05-87ER40309, Rice University) and (W-7405-ENG-36, Los Alamos National Laboratory).

References

- [1] J. Rafelski, Phys. Lett. B 91 (1980) 281; Nucl. Phys. A 418 (1984) 215c.
- [2] W.R. Gibbs and D. Strottman, Proc. Intern. Conf. on Antinucleon- and nucleon-nucleon interactions (Tallahassee, CO, March 1985) (Plenum, New York); W.R. Gibbs, Proc. Fermilab Workshop on Low-energy antiproton physics, Proc. Conf. on Intersections between

- particle and nuclear physics (Lake Louise, Canada, 1986).
AIP Conf. Proc. No. 150 (AIP, New York) p. 505.
- [3] K. Miyano et al., Phys. Rev. Lett. 53 (1984) 1725.
 - [4] D. Strottman and W.R. Gibbs, Phys. Lett. B 149 (1984) 288.
 - [5] S. Noguchi et al., Z. Phys. C 24 (1984) 297.
 - [6] L. Bachman et al., Nucl. Phys. B 263 (1986) 258.
 - [7] H. Becker et al., Nucl. Phys. B 141 (1978) 48.
 - [8] G.D. Patel et al., Z. Phys. C 12 (1982) 189.
 - [9] M.T. Regan et al., Nucl. Phys. B 141 (1978) 65.
 - [10] B.R. French et al., Nucl. Phys. B 119 (1977) 237.
 - [11] S.N. Ganguli et al., Nucl. Phys. B 53 (1973) 458.
 - [12] S. Banerjee et al., Nucl. Phys. B 150 (1979) 119.
 - [13] B. Jayet et al., Nuovo Cimento 45A (1978) 371.
 - [14] D.J. Millener, C.B. Dover and A. Gal, Phys. Rev. C 38 (1988) 2700.
 - [15] CERN-HERA reports 83-01, 83-02, 84-01.
 - [16] J. Rafelski, Phys. Lett. B 207 (1988) 371.
 - [17] C.M. Ko and R. Yuan, Phys. Lett. B 192 (1987) 31.
 - [18] C.B. Dover and P. Koch, Proc. Conf. on Hadronic matter in collision (Tucson, AZ, October 1988).
 - [19] J. Cugnon, P. Deneye and J. Vandermeulen, Liege preprint (1989).

Neutral V Production with $14.6 \times A$ GeV/c Silicon Beams*

S.E. Eiseman, A. Etkin, K.J. Foley, R.W. Hackenburg, R.S. Longacre,
W.A. Love, T.W. Morris, E.D. Platner and A.C. Saulys
Brookhaven National Laboratory, Upton, New York 11973

S.J. Lindenbaum
Brookhaven National Laboratory and City College of New York

C.S. Chan, M.A. Kramer and K. Zhao
City College of New York, New York, New York 10031

T.J. Hallman and L. Madansky
Johns Hopkins University, Baltimore, Maryland 21218

B.E. Bonner, J.A. Buchanan, C.N. Chiou, J.M. Clement, M.D. Corcoran,
J.W. Kruk, G.S. Mutchler, F. Nessi-Tedaldi, M. Nessi and J.B. Roberts
Rice University, Houston, Texas 77251

Submitted to Physics Letters B

May 30, 1990

* This research was supported by the U.S. Department of Energy under Contract Nos. DE-AC02-76CH00016, DE-AC02-83ER40107, DE-AS05-81ER40032 and DE-AC02-76ER03274, and the City University of New York PSC-BHE Research Award Program.

Neutral V Production with $14.6 \times A$ GeV/c Silicon Beams *

S.E. Eiseman, A. Etkin, K.J. Foley, R.W. Hackenburg, R.S. Longacre,
W.A. Love, T.W. Morris, E.D. Platner and A.C. Saulys
Brookhaven National Laboratory, Upton, NY 11978

S.J. Lindenbaum
Brookhaven National Laboratory and City College of New York

C.S. Chan, M.A. Kramer and K. Zhao
City College of New York, New York, NY 10031

T.J. Hallman and L. Madansky
Johns Hopkins University, Baltimore, MD 21218

B.E. Bonner, J.A. Buchanan, C.N. Chiou, J.M. Clement, M.D. Corcoran,
J.W. Kruk, G.S. Mutchler, F. Nessi-Tedaldi, M. Nessi and J.B. Roberts
Rice University, Houston, TX 77251

Abstract

We present the results of a measurement of neutral vee production with $14.6 \times A$ GeV/c Si beams on Au and Cu targets. The Λ and K_s^0 yields were measured as a function of negative particle multiplicity. Effective temperatures were determined from an exponential fit to the transverse mass distributions.

* This research was supported by the US Department of Energy under Contract Nos. DE-AC02-76CH00016, DE-AC02-83ER40107, DE-AS05- 81ER40032 and DE-AC02-76ER03274, and the City University of New York PSC-BHE Research Award Program.

1. Introduction

It was suggested some time ago¹ that enhanced strange particle production would be a good signal for production of a Quark-Gluon Plasma in heavy ion collisions. More recently, questions² have been raised as to how the expected excess of strange quarks would translate into observable particles. An enhancement of K^+/π^+ ratio in $14.6 \times A$ GeV/c Si-Au interactions and an enhancement of Λ 's, $\bar{\Lambda}$'s and K_s^0 's in $200 \times A$ GeV/c S-S interactions compared to that expected from a superposition of nucleon-nucleon interactions have been reported.^{3,4} Clearly, further theoretical and experimental studies are needed to determine the characteristics of such signals. We have measured Λ and K_s^0 production in Si-Au and Si-Cu collisions at $14.6 \times A$ GeV/c at the BNL AGS. We report here on a sample of ~ 750 Λ events and ~ 300 K_s^0 events from the Au target and ~ 850 Λ events and ~ 400 K_s^0 events from the Cu target.

2. Experimental Method

The experiment used three TPC (Time Projection Chamber) modules⁵ in a 5 KGauss magnetic field to measure charged particles in the forward hemisphere in the center-of-mass, or from 0 to 20° in the lab. The experimental arrangement is shown in Figure 1. The incident silicon ions were identified by a plastic Čerenkov counter. The trigger was based on a scintillation counter 8 meters downstream of the target to veto on high Z fragments in the beam region and a pair of counters 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 ion beam line. Events were recorded requiring signals in both counters behind the target and a veto counter trigger level corresponding to $Z \leq 6$. The veto counter pulse height, which was recorded for further event selection, was found to correlate with the multiplicity of the events. To obtain a sample of centrally enriched events, triggers were selected which had a signal in the veto counter of less than 2 times minimum ionization. These events are referred to as "central" events. Target thicknesses were selected to be $< 1\%$ radiation lengths in order to minimize gamma ray conversions that would give incorrect multiplicities. A 25 micron Au target and a 125 micron Cu target

were used. Since the beam passed directly through the center of the TPC's, the beam rate was ~ 5000 ions/sec. in order to limit the amount of ionization deposited in the TPC's.

3. Data Analysis

Events were reconstructed, with multiplicities of charged tracks ranging up to 90, using a three-dimensional tracking program. An isometric view of tracks in the TPC modules from a typical Si-Au interaction is shown in Figure 2. Tracks which missed the production point by more than 7 mm were selected as candidates for decay vertices. In order to obtain a good signal to background ratio the decay distance was required to be > 10 cm and the reconstructed momentum vector had to point back to the production vertex within 2.5 mm. The positive and negative tracks were then assigned the relevant masses for Λ and K_s^0 decays and the effective mass of the pair was calculated. Figure 3 shows the π^-p effective mass distribution. A clear peak is seen at the Λ mass. Vertices with effective mass range of 1.106 to 1.126 GeV/c^2 were selected as Λ 's. Figure 4 shows the $\pi^+\pi^-$ effective mass distribution, with vertices removed if the Λ mass hypothesis is satisfied. The K_s^0 peak is evident. Vertices with effective mass range of .475 to .525 GeV/c^2 were selected as K_s^0 's. In both cases the events in the tails of the effective mass distributions were used for background subtractions. The $\pi^+\bar{p}$ hypothesis yields no statistically significant $\bar{\Lambda}$ signal. The observed limit on $\bar{\Lambda}$ production is $N(\bar{\Lambda})/N(\Lambda) < 0.07$ (95% C.L.).

In order to calculate acceptances for the V^0 's satisfying the above mentioned cuts, a complete Monte Carlo simulation of events was performed using GEANT3. Events were generated using a modified HIJET⁶ model. The resultant 4-momenta of the generated tracks were used as input to the GEANT3 program, which did the tracking in a magnetic field. The generated hits included all the known effects of detector apertures, efficiencies, resolutions and distortions. The output of the GEANT3 program was in identical format to the actual raw data format. The results of this simulation were then analyzed by the same program used to analyze the actual data. The output of this analysis provided the numerator for the acceptance calculation, while the input provided the denominator.

4. Results

The acceptance corrected decay distributions of Λ 's and K_s^0 's for our Au data are shown in Figure 5 as a function of ct . The solid lines are not fits, but the known lifetimes. They agree with our data reasonably well, which gives us a check on our acceptance calculations.

In order to deduce the characteristics of the data we have limited our analysis to regions of rapidity that have reasonably uniform acceptance. We chose $1.2 < y < 3.0$ for Λ 's and $2.2 < y < 3.0$ for K_s^0 's, where the acceptance averages $\sim 15\%$. Negative particles that go through at least the first TPC module and have a π^- rapidity > 1.7 have a good acceptance in our apparatus. We have chosen the multiplicity of these negative particles, which ranges up to ~ 20 for both Au and Cu, as a measure of the energy deposited in the interaction. The absolute scale of this multiplicity is not relevant for the following discussions. It is only important to note that the highest multiplicities correspond to the most central events.

The Λ yield per event, corrected for neutral branching ratio, is shown as a function of this multiplicity in Figure 6. The K_s^0 yield is shown in Figure 7. The yields show a monotonic increase with increasing multiplicity, hence the largest yields correspond to the most central events. The highest multiplicity bin corresponds to 0.28 barns interaction cross section for Au and 0.16 barns for Cu. We estimate an overall systematic uncertainty in this cross section of $\sim 20\%$. The yields per negative particle for this selected multiplicity are shown in Figure 8. Both Λ 's and K_s^0 's show, within statistics, a constant yield per negative particle as a function of this multiplicity. An increase of Λ 's, $\bar{\Lambda}$'s and K_s^0 's as a function of negative particle multiplicity has been also observed in S-S collisions at $200 \times A$ GeV/c.⁴ Because of the different energy and kinematic regions a quantitative comparison is difficult.

The predictions of the current version of the HIJET model with all the known meson-nucleon rescattering channels included are shown in Figures 6 and 7 with open symbols. The agreement is good for the Λ 's, but the slope of the increase is still flatter in HIJET. In order to achieve this agreement we had to set the formation time of secondaries to zero which maximizes the rescattering. The K_s^0 's show a substantial disagreement with the

data, but with the addition of meson-meson rescattering to HIJET we expect a better agreement.

In Figure 9 we plot $[1/N_{ev}][dN/dp_T^2]$ vs. m_T ($m_T = [m^2 + p_T^2]^{1/2}$) for Λ 's and K_s^0 's from both Au and Cu targets. The m_T ranges correspond to a transverse momentum range of $0 < p_T < 1.0$ GeV/c. Clearly all of the data is represented by exponentials. The events are in the above mentioned rapidity ranges and in the central cut as mentioned in section 2. The inverse slopes are listed as temperatures in Table 1. Errors are statistical only. We estimate an additional systematic uncertainty of 20%.

5. Conclusions

We find that Λ and K_s^0 production in interactions of Si on Au and Cu targets at $14.6 \times A$ GeV/c increases monotonically with increasing charged multiplicity for negative particles produced in nucleon-nucleon center of mass in the forward hemisphere for $1.2 < y(\Lambda) < 3.0$ and $2.2 < y(K_s^0) < 3.0$. The yield per forward negative particle is independent of multiplicity and does not differ much between Au and Cu targets. The effective temperature for the "fireball" is found to be ~ 150 MeV for Λ 's and K_s^0 's on both Au and Cu targets. The modified HIJET model with meson-nucleon rescattering using zero formation time reproduces the Λ yields reasonably well without the necessity of introducing any new phenomena.

Acknowledgements

We wish to thank the members of the AGS and MPS staff for their support during this experiment.

References

1. J. Rafelski and R. Hagedorn, in Thermodynamics of Quarks and Hadrons, Ed. H. Satz (North Holland, Amsterdam, 1981).
P. Koch, B. Müller and J. Rafelski, Phys. Rep. C142 (1986) 167.
2. B. L. Friman, Nucl. Phys. A498 (1989) 161c.
3. T. Abbott et al., Phys. Rev. Lett. 64 (1990) 847.
4. J. Bartke et al., Institut für Kernphysik preprint IKF90-2 (submitted to Zeitschrift für Physik C).
5. A. Etkin et al., Nucl. Instr. and Meth. in Phys. Research A283 (1989) 557.
6. A. Shor and A. Longacre, Phys. Lett. B218 (1989) 100.

Figure Captions

FIG. 1 Plan view of the apparatus.

FIG. 2 Reconstructed tracks in the TPC modules for a typical Si-Au interaction.

FIG. 3 Effective mass spectrum for π^-p hypothesis for the Au target data.

FIG. 4 Effective mass spectrum for $\pi^+\pi^-$ hypothesis for the Au target data.

FIG. 5 Λ and K_s^0 lifetime plots for the Au target data. The solid lines are the known lifetimes.

FIG. 6 Λ yield in the rapidity region $1.2 < y < 3.0$ as a function of negative track multiplicity as described in text. The errors shown are statistical only.

FIG. 7 K_s^0 yield in the rapidity region $2.2 < y < 3.0$ as a function of negative track multiplicity as described in text. The errors shown are statistical only.

FIG. 8 V^0 yield per selected negative track as described in text. The errors shown are statistical only.

FIG. 9 Transverse momentum distributions as a function of transverse mass m_T for Λ 's and K_s^0 's from both Au and Cu targets. The errors shown are statistical only.

TABLE 1

Effective temperatures derived from an exponential fit to the transverse mass for Λ 's and K_s^0 's from both Au and Cu targets.

Temperatures (MeV)		
	Au	Cu
Λ	152 ± 7	159 ± 13
K_s^0	149 ± 13	135 ± 18

MPS E-810 Detectors

Plan view

Run 6
Tape 14632
Date 25 JUN 89
Time 07:47:09
Event 16

Si on Au Data

Si on Au Data - Λ removed

Si on Au - V^0 Lifetimes

Λ Data ($1.2 < y < 3.0$)

K^0_s Data ($2.2 < y < 3.0$)

V^0 Yield/negative prong

Si on Au & Cu - Λ & K_s^0 p_T Distributions

- END -

DATE FILMED

11 / 02 / 90