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HIGH ENERGY PHYSICS AT THE UNIVERSITY OF IOWA

Progress Report

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TASK A

Study of Electron Proton Physics
with ZEUS at HERA

U. Mallik, Professor,
Co-Principal Investigator

E. McCliment, Professor,
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Progress Report of Activity for the Year 1993 and Proposal for 1994; Study of Electron Proton Physics with ZEUS at HERA

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Task A: HERA/ZEUS

U. Mallik (Professor)

E. McCliment (Professor)

The year 1992 saw the successful turn on of the electron-proton collider HERA and the beginning of exploration of the new physics domain that becomes accessible. The physics results published to date by the ZEUS experiment are listed in the reference section. The collider has performed very well, producing an integrated luminosity of $\sim 3\text{nb}^{-1}$ in the summer and $\sim 27\text{nb}^{-1}$ in the fall, respectively. The 1993 run started in June with a projected accumulated luminosity of $\sim 500\text{nb}^{-1}$ (on tape) by the beginning of November. The machine is performing with 60 bunches for each beam and with a typical electron and proton current of $\sim 13\text{mA}$ and $\sim 10\text{mA}$, respectively. The electron beam energy is 26.6 GeV and the proton beam energy is 820 GeV. A peak luminosity of $1.8 \times 10^{30}\text{cm}^{-2}\text{s}^{-1}$ has been achieved to be compared to the design luminosity is $1.5 \times 10^{31}\text{cm}^{-2}\text{s}^{-1}$, a remarkable achievement so early in the life of a novel machine.

This report describes the activity of the Iowa group, which now consists of two faculty members, Usha Mallik (Professor) and Edward McCliment (Professor), two postdoctoral fellows and three graduate students. Min-Zu Wang, previously a graduate student, completed the requirements for a Ph.D. degree from The University of Iowa in May 1993 and is presently working as a postdoctoral fellow (replacing Tim Bienz). Hubert Kreutzmann, the second Iowa postdoctoral fellow of the group left in April 1993 and has been replaced by Yangling Zhang in July. Maria Roco is in the process of completing her analyses and writing a thesis for her Ph.D. degree. The two other graduate students Song-Ming Wang and Jia-Tai Wu have successfully completed the comprehensive exam in September

1993; Jia-Tai is resident in DESY from October 1993, and Song-Ming is expected to join him in November in DESY following the completion of a course. Song-Ming Wang is now working under the guidance of Usha Mallik (is presently being supported by McCliment). Ed McCliment is spending a year of sabbatical starting in July 1993, and Usha Mallik is spending the last semester of the Faculty Scholar Award leave from June 1993 to December 1993 in DESY. Mallik expects to return to DESY for the academic year of 1995.

The current report which describes the past and present activity of this group and the future plans is divided into the following chapters: a short description of ZEUS, the physics contribution, which consists of the preparation and analysis for the search for J/ψ in the 1993 data, analysis of the 1992 ZEUS data, participation in future ZEUS upgrade foreseen for 1994/1995, and maintenance and running of ZEUS. McCliment's Fermilab work is described at the end.

1. Description of the ZEUS Detector

The University of Iowa joined the ZEUS experiment at the electron-proton (e-p) collider HERA in November 1988. This report will assume that the readers are familiar with HERA and ZEUS, but a short description of the detector, especially, the features newly working for the 1993 run is given here for convenience.

Figure 1a,b show an azimuthal and an axial view of the ZEUS detector. Details of the ZEUS detector can be found elsewhere.^[1] Most detector components are divided into three sections, Barrel (prefix B) or Central (prefix C), Forward (prefix F), and Rear (prefix R).

A VerteX Detector (VXD) is implemented outside the beampipe and inside the Central Tracking Detector (CTD). It consists of 120 cells of long wires stretched parallel to the beam in a carbon fiber vessel filled with Dimethylether. It has been working since 1992.

Tracking is achieved by Tracking Detectors, CTD, FTD and RTD. The CTD is a cylindrical, nine superlayer drift chamber with each superlayer containing eight layers of

sense wires for position and energy loss measurement. All nine superlayers are instrumented and working in the 1993 run. A position resolution of $\sim 230\mu\text{m}$ ($\sigma_{r\phi}$) has been presently achieved where the design goal is $120\mu\text{m}$. The FTD and RTD consist of planar drift chambers; with Transition Radiation Detectors (TRD) interspersed in the FTD for electron identification. A superconducting solenoid (COIL) surrounds the CTD and can provide a magnetic field of up to 1.8 Tesla, but has been kept at 1.43 T. A major fraction of the FTD ($\sim 75\%$) sense wires are read out, and in early October both the FTD and the TRD readouts will be tested.

The 'Heart of ZEUS' has been a state-of-the-art, high resolution, fully compensating Uranium-scintillator calorimeter constructed with alternate layers of 3.3 mm thick Depleted Uranium (DU, U_{238} with U_{235} depleted) as the passive absorber and 2.6 mm thick plastic scintillator as the active material. The calorimeter is divided into three sections, the ElectroMagnetic Calorimeter (EMC), Hadronic Calorimeter sections (HAC1 and HAC2). Each of the FCAL and the BCAL modules consists of an EMC section (1λ in thickness), and two HAC sections (3λ each in thickness for FCAL and 2λ each in thickness for BCAL), while an RCAL module consists of one EMC section (1λ) and one HAC section (3λ). At a depth of $3X_0$ in the REMC, a Rear Hadron Electron Separator (RHES) has been installed with electronics to be completed in 1993/1994 winter shut-down. A fraction of the RHES ($\sim 30\%$) has been active in the 1993 run. The calorimeter has been a remarkable success as evidenced by the 1992 data and performed according to the design.

The American part of the ZEUS collaboration (AMZEUS) has constructed the BCAL and the CAL readout electronics. The BCAL modules and the readout electronics were calibrated at the Fermilab experiment, E790.^[2] AMZEUS is also responsible for the CAL first level trigger of ZEUS which has been installed for the 1993 run.

The iron yoke for the return path of the magnet acts as the absorber for the BACKing Calorimeter (FBAC, BBAC, RBAC). This, in combination with layers of streamer tubes run in proportional mode, interspersed in the iron, catch and measure the leakage energy.

Muon identification is achieved by the MUon detectors, inner and outer layers,

BMUL, BMUO, RMUL, RMUO, FMUL, FMUO, and the forward muon spectrometer. Muons are detected in the forward direction using drift and limited streamer tube chambers and scintillation counters interspersed between the magnetized iron yoke and the magnetized iron toroids. In the central and rear direction limited streamer tubes are placed between and behind the concrete shield. All of BMUON have been operational for the 1993 run. All of FMUON is installed and most of it is operational for the 1993 run.

The Leading Proton Spectrometer (LPS) consists of six stations of silicon detectors above and below the beam line between 20 and 90 meters from ZEUS in the Forward direction. They contain silicon strips at a pitch of $\pm 125\mu\text{m}$. Four of these stations have been implemented to date.

A BeamPipe Calorimeter (BPC) of alternate layers of W absorbers and silicon strips has been instrumented in the Rear direction ~ 3 meters from the IP.

Future upgrades planned for ZEUS are described later.

2. Physics from ZEUS

The Physics groups currently are : i) Structure Function, ii) Hadronic Energy Flow, iii) Soft Photoproduction, iv) Boson Gluon Fusion, and v) Exotics. A new group of Heavy Flavor has been started from September 1993 as the sixth group.

2.1. J/ψ SEARCH IN 1993

Iowa has been interested in the J/ψ search. The goal from the 1993 data is to measure the production cross section at HERA energy which is hitherto unknown and will lead to an estimate of the Gluon Structure Function. The J/ψ is identified in its leptonic decay modes, i.e., $\mu^+\mu^-$ and e^+e^- , with a reasonable branching fraction ($\sim 6\%$ in each leptonic mode^[1]). The production cross section, from measurements to date, is expected to be very small^[4] ($\sim \text{few nb}$), hence, ~ 10 decays are expected to be detected in 1 million events collected.

2.1.1. TRIGGER

Presently the J/ψ search is part of the Heavy Flavor Group. Until September 1993, the J/ψ group was a subgroup of the Boson Gluon Fusion (BGF) group. Hence, the J/ψ triggers (elastic and inelastic) have also been defined as subtriggers in the BGF section for the 1993 data taking period. Usha Mallik and Min-Zu Wang from Iowa have been intimately involved in the trigger configurations in the First Level Trigger (FLT) and the Third Level Trigger (TLT). In the course of the data taking, under the evolving conditions of luminosity and experimental configurations, the trigger setup was also evolving, especially for the new physics like this which makes critical use of the newly completed CTD. The final configuration for 1993 FLT and TLT are in place. The detailed history of the J/ψ triggers is described in ZEUS-Note 93-105 (in preparation), an (unfinished) early draft of which is appended. The TLT algorithm now in place was entirely done by Min-Zu Wang and brought the trigger rate down successfully for the inelastic channels, by using a simple algorithm of track and calorimeter cluster matching.

2.1.2. FILTER

As mentioned earlier, the expected ratio of signal to the triggered events is $\sim 1:10^5$. An offline filter program, based on a similar philosophy, but with improved quality of track and cluster matching, has been provided by Min-Zu Wang. This filter typically reduces the data volume to 2%. (As described later in the analysis, the success of the filter was manifested in the nice J/ψ peaks observed in both e^+e^- and $\mu^+\mu^-$ decay modes). This fast offline filter and the TLT algorithm were tested by a more sophisticated algorithm by Yangling Zhang and Usha Mallik using Runge Kutta method of extrapolating the tracks to the calorimeter and then matching with the calorimeter 'islands' (a cluster algorithm) and using the calorimeter energy deposit to identify leptons. Comparing these results, Wang was able to vastly improve the TLT efficiency.

The ZEUS offline reconstruction program has been modified several times in the course of the data taking. The final set of CTD constants are not available yet. However, the tracking software as well as the constants have been improved sufficiently such that

the data accumulated thus far and that yet to be accumulated in this run period will be (re)processed in very near future in order to have a homogeneous processing of the complete data sample. The reprocessing program will incorporate as many improvements as are currently available. To this end Ed McCliment and Min-Zu Wang are working towards an improved J/ψ filter to be used for the reprocessing. McCliment is also involved in a thorough understanding of the TLT algorithm which is critical to measure its efficiency. (The FLT efficiency has been and is being studied by Canguo Li, a graduate student from OSU.)

2.1.3. ANALYSIS OF 1993 DATA

Resources: The ZEUS central analysis computing facility ZARAH* has been very helpful in processing DSTs for further analysis. The filter program at the end of the reconstruction job sets up tags if a particular event is wanted by any one of the analysis group. These events are selected for detailed 'level 2' processing and the results are stored on ZARAH disk in the form of miniDST. Currently this requires ~ 13 kByte per event, however, soon this will be increased to ~ 19 kByte as raw data of CTD will also be stored in the miniDST to facilitate further reprocessing.

Iowa presently has three Silicon Graphics workstations, two Indigo 3000 and one Indigo2 4000 with 35 mips and 70 mips processing powers, respectively. It also has 14 GByte disk space with four high density exabyte tape drives available. This has enabled the group to have a complete data sample of J/ψ 's with 'improved' filter.

Analysis : Min-Zu Wang and Usha Mallik are performing two independent sets of analyses. Presently, Wang is analyzing the two prong (primarily elastic) events and Mallik is working with higher multiplicity events, primarily the inelastic events. Figures 2a and b show the invariant mass distributions of two electrons and two muons, respectively, from the filtered data sample. A peak is clearly visible at the J/ψ mass. The efficiency of the muon decay mode is low as indicated by the Monte Carlo study. The plot represents

* it consists of a powerful cpu server with very high data processing bandwidth and is equipped with large disk based data storage with fast, high capacity tape storage. It is designed for processing DSTs and producing miniDSTs with batch service.

data from a luminosity of $\sim 220 \text{ nb}^{-1}$. A minimum of $0.8 \text{ GeV}/c$ transverse momentum requirement has been applied to these events. All the events at and near the J/ψ peak have been individually inspected. Figures 2c and d show two such one event displays. The corresponding Monte Carlo expectations for the J/ψ events are displayed in Figures 3(a,b). Figures 4a and b plot the transverse momentum distribution from the data and from the J/ψ Monte Carlo, respectively. A clear preference for higher transverse momenta is observed for the J/ψ events. While the presence of the J/ψ 's is seen, it is harder to obtain a clear signal for the high multiplicity sample.

Future plan of analysis: The critical next step is to determine the combined efficiency and acceptance of the event selection. This includes study of the various generators and the hadronization processes. Zhang is presently trying to setup and optimize a package which will identify leptons as part of the matching of tracks and clusters. In short, the study has just begun.

2.2. ANALYSIS OF 1992 DATA

The physics results from the 1992 data from ZEUS has been described elsewhere (see reference section). One of the most exciting results of 1992 data is the extraction of the Structure Function F_2 in the recent HERA explored low x domain; figure 5 and 6 show the results from the F_2 publication. The data seems to follow the MRSD-' extension into this region indicating no saturation effect is observed yet in the current data.

Maria Roco has been working in the Structure Function group with the 1992 data. She is preparing for a Ph.D. thesis which primarily contains her work on the study of the kinematic variables for the F_2 measurement and the first look at the gluon density distribution. The anticipated graduation date is May 1994. It is expected that she will present the results from ZEUS at a conference in early spring.

2.2.1. STUDY OF DETECTOR SYSTEMATICS

A precise reconstruction of the kinematical quantities is crucial in the determination of the proton structure function. This involves a thorough understanding of the electron and hadronic energy scales. Errors in the energy measurements of the electron and hadrons would result in systematic shifts in x and Q^2 which might severely affect the proton structure function determination. Due to detector effects such as inactive material, beamhole, calorimeter boundaries and calorimeter noise, the measured energies in the detector are in general lower than the true (generated) values in the Monte Carlo. The loss in the hadronic transverse momentum as well as the hadronic E_{pz} is $\sim 15 - 20\%$. In order to understand where this deficiency is coming from, a study was done to estimate how much of the loss is due to the beamhole and the inactive material. In addition, corrections to the hadronic quantities were extracted which would compensate for these losses. The details of the work is described in the appended ZEUS-Note 93-064/U. of Iowa Pub 93-13 by Maria Roco.

2.2.2. EXTRACTION OF GLUON DENSITY DISTRIBUTION

The gluon distribution cannot be directly measured in deep inelastic lepton hadron scattering since gluons do not carry weak or electric charge. However, there are methods proposed to indirectly measure the gluons in the nucleon. The method used in this analysis is based on the assumption that at small values of the Bjorken scaling variable $x \leq .01$, the QCD predicted F_2 scaling violations arise mainly from the gluon density. The results from the ZEUS proton structure analysis, showed an observed dependence of F_2 on Q^2 which is in accord with the scaling violations predicted by QCD, as displayed in Fig.7. The procedure and the derivation of the systematic errors involved are discussed in the appended internal ZEUS report by Roco in ZEUS-NOTE 93-088/U. of Iowa Pub 93-14.

2.2.3. EXTRACTION OF F2

Roco is presently performing an independent extraction of F2 as part of her thesis. The determination of the systematics is one of the most critical aspects of the results. She is making an independent evaluation of the systematics, which involves a thorough understanding of the uncertainty arising from the determination of the hadronic energy scale and various electron finding algorithms: the electron energy and the position measurements, estimation of photoproduction background in the DIS event sample, different tracking algorithms, vertex determination and the use of various structure function inputs.

3. Future Upgrade of ZEUS

As the luminosity approaches the design value, new and better measurements are needed to study low cross section phenomena and to observe precise results. To this end, several upgrades of the ZEUS detector, not included in the original design, are now underway; they are:

1. Small Angle Rear Tracking Detector (SRTD): As discovered from the 1992 data, the electromagnetic clusters around the beam pipe (20cm X 20cm) were not properly understood and subsequently, were discarded from the event sample. This caused poor electron measurements and therefore severe limitations of statistics. To remedy the situation, the SRTD was planned to be installed for 1994 data taking. It consists of two layers of 1 cm wide scintillator strips (X and Y) in front of the REMC as shown in Figure 8; an identical readout to that of the calorimeter is used. A prototype has been installed in the 1993 run and is working.
2. Forward Neutron Calorimeter (FNC): One of the exciting observations from the 1992 data has been the events with a large rapidity gap (see reference section). The Regge type exchanges have been revived with newer QCD interpretations. To test any possible One Pion Exchange (OPE) model, the construction of the FNC for implementation in the 1994 data taking has been proposed to the PRC in the

form of a letter of intent. The FNC will consist of a plastic scintillator sampling calorimeter $\sim 10\lambda$ deep at a distance of 100-120 meters from the IP in the Forward direction in the beamline covering 60cm X 60cm area. A prototype is being tested in the 1993 run.

3. Presampler: The thickness of the dead material encountered by a particle emerging from the ZEUS interaction point varies as a function of the polar angle θ (Fig.9) leading to an energy loss of the particles traversing the dead material. In principle this effect can be corrected on average if all the effects in the detector are properly simulated in the Monte Carlo. However, to have a correction on an event-to-event basis, a presampler of the showers produced in the dead material is proposed. It consists of scintillator tiles with WaveLength Shifter (WLS) fibers leading to PMTs as shown in Fig.10 for a (10cmX10cm) prototype. The details of the presampler is described in DESY PRC 93-07 and is appended to this report; it was presented to the Program Review Committee (PRC) at the end of September 1993 in the form of a letter of intent. Iowa's role in the project is described below.

Presampler : Iowa's role

The idea of a presampler has been around for nearly two years. A few beam tests at CERN have established the feasibility of the basic design, i.e., 20cm X 20cm X 0.5cm scintillator tiles with 2mm WLS fibers glued in the scintillator tiles. The type of PMTs and the kind of readouts are still under discussion. The two previous options, namely, a digital pipeline and an optical delay line (described in the appended report), are exciting and are undergoing tests which show promise. However, as they are new to ZEUS, it will be virtually impossible to have an established system integrated in the ZEUS data chain using either of these options by 1995 data taking or a prototype with a few channels installed for the 1994 data taking.

Iowa volunteered to explore an alternative; a modification of an already established readout system, namely, that of the RHES. The outputs of the silicon diodes are preamplified and shaped which produces a (differentiated) bipolar pulse with 180 ns rise time; the first half of the bipolar pulse is sampled and digitized to yield the charge and the time

signal. The pulse shape input to the shaper and output pulse from the shaper are shown in Figure 11. (The input to the shaper has a $20\text{ K}\Omega$ impedance). Whether a PMT output signal can be successfully shaped and measured using a shaper with such a long rise time was an important concern. At DESY, Mallik, McCliment, Wang and Zhang with help from a HES expert successfully observed PMT outputs through the HES shaper with an oscilloscope.

As the presampler will be placed in front of the (SRTD/)RCAL and the FCAL, it will be exposed to substantial Uranium noise. To test if this will in any way hurt the feasibility of the measurements, Wang and Zhang participated in a beam test scheduled at CERN in August 1993 to study the energy deposits in the presampler placed in front of the FCAL prototype with materials of various thickness placed in the beam line in front of the presampler. Figures 12 summarize the results for a 30 GeV electron beam and demonstrate the success of the endeavor. The specific details regarding the exact gain, dynamic range, resolution, linearity, charge and time reconstruction algorithms and calibration schemes need yet to be established more quantitatively with the final designs, e.g., the type of PMT to be used (a multianode PMT is under study by Zeuthen). The primary cost will be shared by NIKHEF and Zeuthen. It is worth noting that with the success of the implementation of the HES shaper, the Forward Neutron Calorimeter (FNC) is also considering a similar readout scheme.

4. Maintenance and run

The Iowa group has been a prime contributor in preparation and commissioning of the ZEUS experiment. This includes Data Validation, Calorimeter Data Quality Monitoring (DQM), shiftwork, BCAL infrastructure and BCAL safety.

4.1. DATA VALIDATION

Last year Mallik and Kreutzmann were responsible for the quasi-online check of the data collected by ZEUS. As the online tests of each part of the detector matured, it was foreseen to have the data validation merge with the offline data reconstruction, thereby incorporating some detailed checks prior to the 1993 run. To this end, Kreutzmann worked with Matthias Kasemann, the offline coordinator and his deputy Frank Zetsche, from November 1992 till April 1993. The transition took place smoothly and the data validation shifts were freed up for the 1993 run. A few examples of some plots for the CAL monitoring are presented in Fig.13.

4.2. CAL (DQM) AND ONLINE MAINTENANCE SHIFTS

The ZEUS calorimeter DQM has been enlarged and modified to include other calorimeter subsystems, e.g., the FLT and SLT. Altogether there are fourteen people on shift round the year, seven of whom are CAL experts. One expert and one non-expert is on shift every week, they are on call 24 hours, seven days a week during their shift. They perform calorimeter checkout runs once everyday, this includes Uranium current measurement, pedestal runs and charge injector runs. A laser test run is also performed. Partial calibration is performed and the dead channel list updated and supplied to the offline everyday. If any broken readout can be fixed without an access, it is done. If a window of opportunity for a full calibration of the calorimeter exists during the scheduled run time, this is also performed. Some of the previous data validation for the calorimeter has been split off and serves as part of the DQM. Checking the CAL diagnostic plots from the reconstruction outputs is the shift person's responsibility. This includes checking for transmission errors (from TLT to IBM) and parity errors from the digital cards. Min-Zu Wang has served as an expert. Many of the diagnostics for raw data for offline programs are supplied and incorporated into DQM by him. The DQM shift reports the status of the calorimeter daily at the 3:30 pm meeting in the ZEUS hall and weekly in the ZEUS calorimeter meeting.

4.3. CFLT MONITOR

The FLT part of the existing DQM tests the trigger output integrated over the energies from whole modules, each of which includes many individual trigger towers. To check if individual towers are working properly, and also as a quick check for miscabling (major work on the calorimeter is scheduled during the winter shutdown), McCliment is working with D. Krakauer from ANL on software that will enable one to put charge corresponding to a given energy into each trigger tower separately and check that the output trigger information corresponds to the input energy. This software has been tested with stand-alone charge-injection runs of the calorimeter. But it still needs to be integrated with the online software. A preliminary test has shown that charge can be correctly distributed equally to all the phototube inputs of a single trigger tower. This is shown in Fig.14. This figure shows the online histograms of energy reported by the first level trigger corresponding to 10 GeV energy input to a single tower in Module 6 of the calorimeter. It will be noted that the energy in Module 6 correctly lies between 8 and 12 GeV in agreement with the input. Further work is in progress to be able to download successively more than one tower.

4.4. SHIFT WORK

The ZEUS shifts consist of four people: a shift leader, a deputy shift leader, an online operator and a safety person. Iowa has taken its full share of the deputy and the safety shifts.

4.5. INFRASTRUCTURE AND SAFETY OF BCAL

Three people are responsible for maintenance of the infrastructure; two are from FCAL/RCAL and one from BCAL. This person organizes the work schedules in the calorimeter prior to any scheduled access to avoid any conflict, e.g., trigger work and readout work; in addition, he/she is also responsible for overseeing the proper maintenance of all CAL related equipments e.g., power supplies and cooling water circulation.

McCliment has been nominated as the BCAL infrastructure person for the present year. He is also performing the duty of the BCAL safety officer.

5. Summary

Iowa has taken a leadership role in Physics projects (gluon density determination, J/ψ production), detector development, and in maintainance and running of ZEUS.

An offline analysis environment has been established in Iowa in January 1993 with a Silicon Graphics (SGI) R4000 Indigo computer, three disks and a high density exabyte tape drive. These are used by the students at Iowa and the resident faculty. The resources at DESY are all SGI which presently consist of two R3000 Indigo's and one R4000 Indigo2 in cpu. The peripherals consist of four hi-density exabyte tape drives and fourteen GByte of HP disks. They have and are continuing to provide very useful service to the group. The Indigo2 is a recent addition, and this year when the R4400 is available from SGI, the two R3000 Indigos will be upgraded to R4400.

It is hoped that the present level of (two postdocs) manpower can be maintained. The two postdocs provide the 'critical mass' to have a visible and an important impact in an experiment like 'ZEUS', and Iowa has more than demonstrated excellence for a group of its size. The Iowa administration is helping maintain the second postdoc by paying half his salary this past year. (The university is additionally contributing by releasing Mallik from teaching for the entire academic year of 1994-95.) The DESY administration feels the need and therefore are eager for DOE to maintain the current personnel level in the Iowa group. It may be possible to persuade them to contribute a few months' support towards initiating DOE in the maintenance of this second postdoc.

The physics yield of ZEUS has only begun; it would be prudent to harvest it with a strong American presence.

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3. Phys. Rev. Lett. 68, 282(1992); 'Calibration of the ZEUS Barrel Calorimeter in a Test beam and A Direct Measurement of the J/ψ Leptonic Branching Fraction', Ph.D. Thesis, M.Z.Wang
4. Phys. Lett. B 258, 493(1991).

ZEUS Publication List

1. Measurement of the Proton Structure Function F2 in ep Scattering at HERA, DESY 93-110, to be published in Phys.Lett.B.
2. Observation of Events with a Large Rapidity Gap in Deep Inelastic Scattering at HERA, DESY 93-093, to be published in Phys.Lett.B.
3. Search for Excited Electrons using the ZEUS Detector, DESY 93-075, to be published in Phys.Lett.B.
4. Hadronic Energy Distributions in Deep Inelastic Scattering Electron-Proton Scattering, DESY 93-068, to be published in Z.f.Physik.
5. Observation of Two-jet Production in Deep Inelastic Scattering at HERA, DESY 93-030, Phys.Lett.B 306 (1993)158.
6. Search for Leptoquarks with the ZEUS Detector, DESY 93-017, Phys.Lett.B 306 (1993)173.
7. Initial Study of Deep Inelastic Scattering with ZEUS at HERA, DESY 92-180, Phys.Lett.B 303 (1993)183.
8. Observation of Hard Scattering in Photoproduction at HERA, DESY 92-138, Phys.Lett.B 297 (1992)404.

9. A Measurement of $\sigma_{tot}(\gamma P)$ at $\sqrt{s} = 210$ GeV, DESY 92-127, Phys.Lett.B 293 (1992)465.

E790 Publications

1. Beam Tests of the ZEUS Barrel Calorimeter, DESY 93-076, to be published in Nucl. Instrum. Method.
2. Proceedings of the International Calorimetry Conference of High Energy Physics, September 1992, Corpus Christi, Texas, USA, by M-Z. Wang et al.

Work on Fermilab Experiment E761

E. McCliment (Professor)

My part of the analysis of E761 data is finished for all practical intents and purposes. My graduate student, Tim Dubbs, and I determined the branching ratio of the rare electroweak decay mode $\Xi^- \rightarrow \Sigma^- \gamma$ from data obtained in the 1990 fixed target run of the Tevatron at Fermilab. We have written a paper on this work, which was submitted to Physical Review Letters. A copy of the title page is included in this report. This paper has been recommended for publication after some minor changes that are presently being taken care of. The work on this project in FY 93 consisted of the following:

1. Finish the simulation of the lead-glass electromagnetic calorimeter;
2. Study of efficiency of cuts to determine the number of cascade lambda pi normalization sample;
3. Final determination of the cascade sigma gamma branching ratio;
4. Study the Systematics;
5. Write the paper.

In addition, Mr. Dubbs was able to finish writing his thesis in time to receive his PhD at the May graduation of the University of Iowa.

Before coming to DESY I also spent a month at Fermilab from mid May to mid June, where I did some work on the new E781 experiment (Production of Charmed Baryons in a Hyperon Beam), which will run in the next fixed target running period, currently scheduled for mid 1995. This work consisted mainly of determining the status of the wire chambers that my colleague, Y. Onel, plans to use in this experiment.

Figure 1a) Schematic view of the central part of the ZEUS detector.

Figure 1b) Section of the detector along the beam.

Figure 2 Invariant mass of two a) electrons and b) muons from the 1993 two-track J/ψ data sample, $\sim 200 \text{ nb}^{-1}$.

Figure 2c) An event display of $J/\Psi \rightarrow e^+ e^-$ candidate.

Figure 2d) An event display of $J/\Psi \rightarrow e^+ e^-$ candidate.

Figure 3 Invariant mass of two a) electrons and b) muons from the reconstructed elastic J/Ψ Monte Carlo sample.

Figure 4 The transverse momentum distribution of the two leptons from a) the 1993 two-track J/Ψ data sample and b) the reconstructed J/Ψ Monte Carlo sample

Figure 5
The structure function F_2 as a function of Q^2 for different values of x ; the F_2 values are multiplied by the factors shown in parenthesis for the different x bins. The statistical errors (inner error bars) and systematic errors added in quadrature (outer error bars) are shown.

Figure 6

The structure function F_2 as a function of x for $Q^2 = 15, 30, 60, 120, 240$ GeV²; also shown are the several structure function expectations (all in the Deep Inelastic Scattering Scheme). The inner error bar is the statistical error and the outer error bar has the systematic error added in quadrature.

Figure 7 The extracted gluon distributions from F_2 scaling violations at low- x . Shown are the statistical errors (inner outer bar) and the systematic errors added in quadrature (outer error bar). The theoretical error is not shown.

Figure 8 The Small angle Rear Tracking Detector (SRTD) and its place in ZEUS.

Radiation length before UCAL

WEEKU:TMC_DEAD_SCAN_NUM10_FINE.HRZ

Figure 9 The thickness of inactive material seen from the Interaction Point (IP) in terms of radiation lengths as a function of polar angle θ .

Figure 10 A prototype of the presampler at the test beam at CERN.

Figure 11 The input and output pulse shapes from the RHES shaper.

Figure 12 Results of the presampler test beam data taken in August 1993 using the RHES shapers for readout for the 30 GeV data; the preshower energies are measured in the presampler. 10, 30 and 70 GeV electron beams were used with material of various thickness in front of the presampler.

Figure 13 Some data validation plots for the calorimeter from the reconstruction program. The two top are the lego and profile plots of energy deposited in FCAL EMC. At the bottom, the distribution of time difference between particles reaching the FCAL and RCAL is shown; the peak at zero corresponds to events taking place at the IP. The last plot shows the E-pz distribution, a small peak at $\sim 2E_e$ characteristic of the DIS events is observed.

Figure 14 ZEUS first level trigger response to charge injection into a single trigger tower in Region 6 of the rear calorimeter. The charge, equivalent to an energy deposit of 10 GeV, is distributed equally among the phototubes of the trigger tower. Bit 5 indicates greater than 10 GeV energy deposit.

TASK B

Fixed Target Experiments at Fermi National Laboratory

C. Newsom, Associate Professor,
Co-Principal Investigator

Y. Onel, Professor,
Co-Principal Investigator

Introduction

The last 12 months have been very fruitful for the Iowa group working at Fermilab and CERN. Our group consists of N. Akchurin (research scientist), A. Bravar (graduate student), J. Chilton (senior undergraduate), D. Kadrmas (graduate student), J. Langland (graduate student), J. McPherson (graduate student), C. Newsom (associate professor), F. Olchowski (graduate student), Y. Onel (professor), T. Wright (senior undergraduate), and in collaboration with E. McCliment (professor).¹ Our research program principally involves data analysis of the physics experiments E-683, E-704 and E-761, and the preparation of E-781. It is a collaborative effort involving The University of Iowa and other research groups.

E-683 investigates the photoproduction of high transverse momentum jets at Wide Band Photon beamline. This experiment's main objective is measuring cross sections of the QCD subprocesses, i.e., QCD Compton effect and quark-gluon fusion.

E-704 is the highest energy (200 GeV) spin physics experiment with incident polarized protons and antiprotons in MP9 Polarized Proton beamline. This experiment focuses on the study of polarization effects in high-energy $pp(\bar{p}p)$ scattering.

Analysis of Fermilab E-761 is yielding large amounts of physics and many papers have been published. Many other papers are in near final draft form. The E-781 (SELEX) test run has been completed successfully and based upon the positive results final approval of that experiment obtained. We will also provide and install the Iowa drift chambers in the E-781 area (6 planes) and 5 MWPC (15 planes). The experiment is now being installed in PC4 at Fermilab. CERN experiments RD17² and WA89 are enjoying similar successes. Analysis results of the WA89 data taken in 1991 are now emerging and look very good, especially in their impact on our experiment at Fermilab, E-781. Additional data was taken in 1993 and the preliminary results look very promising.

Our current commitments include the data analysis of experiments E-683, E-704 and E-761, and research material for three Ph.D. theses.

¹ This work was funded by Task A and reported therein.

² This research was done using both Task B and Task C funds and will be reported on in the Task C section.

E-704

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The E-704 program offers unique spin physics studies at high p_t and large x_t phenomena and also in the difference between total cross sections (pp and $\bar{p}p$) in the pure helicity states at high energies.

During the first part of the 1991–1992 FNAL fixed-target run, we performed the following measurements:

- CNI (Coulomb Nuclear Interference Measurements)
- Polarized-Proton (anti-proton) beam at 200 GeV/c on a polarized target
 - $\Delta\sigma_L(p \uparrow p \uparrow)$ and $\Delta_L(\bar{p} \uparrow p \uparrow)$
 - A_{LL} in $p \uparrow p \uparrow \rightarrow \pi^0 X$ at high p_t
- Polarized-proton beam at 200 GeV/c on a hydrogen target
 - $p \uparrow p \rightarrow \pi^0$ at high p_t
 - $p \uparrow p \rightarrow \Lambda(\Sigma^0)X$
 - $p \uparrow p \rightarrow (\pi^\pm, \pi^0)X$ at large x_t

The primary activities of the Iowa group were the CNI analysis, and the study of spin dependence of Λ with polarized p beam. We are presently the leading institution in both analysis projects.

Coulomb Nuclear Interference (CNI) Measurement

It is commonly believed that polarization in elastic scattering would vanish at high energy where the amplitudes are eventually dominated by diffraction, parametrized in terms of pomeron exchange having no spin-flip terms. However, Schwinger [1] pointed out that large polarization of fast neutrons is possible by the spin-orbit interaction arising from the motion of the neutron magnetic moment in the nuclear Coulomb field at very small scattering angles due to the long-range nature of the electromagnetic interactions. Several authors [2–5] also showed that a small but considerable asymmetry was expected in high-energy pp elastic scattering at small four-momentum transfer squared $|t| \approx 0.003(\text{GeV}/c)^2$ which arises from the interference between the hadronic non-flip and the electromagnetic spin-flip amplitude. In terms of helicity amplitudes, this is expressed as [6,7],

$$A_N \frac{d\sigma}{dt} = -\text{Im}\{(\phi_1 + \phi_2 + \phi_3 - \phi_4)\phi_5^*\} \quad (1)$$

where $\frac{d\sigma}{dt}$ is the spin-averaged differential cross section.

$$\frac{d\sigma}{dt} = \frac{\pi}{2k^2} [|\phi_1|^2 + |\phi_2|^2 + |\phi_3|^2 + |\phi_4|^2 + 4|\phi_5|^2] \quad (2)$$

If the higher order electromagnetic terms are neglected, and under the hypothesis of the additivity of the hadronic and electromagnetic amplitudes, ($\phi_i = \phi_i^h + \phi_i^e$), the differential cross section can be expressed in the Coulomb-nuclear Interference (CNI) region as

$$\frac{d\sigma}{dt} = \frac{d\sigma^e}{dt} + \frac{d\sigma^h}{dt} + \frac{d\sigma^i}{dt} \quad (3)$$

where the superscripts indicate electromagnetic, hadronic and interference contributions to the differential cross section; these are usually parametrized as,

$$\frac{d\sigma}{dt} = \frac{4\pi\alpha^2}{t^2} + \frac{\sigma_{tot}^2}{16\pi} (1 + \rho^2) e^{bt} - \frac{e^{\frac{bt}{2}}}{t} \alpha \sigma_{tot} (\sin 2\delta + \rho \cos 2\delta) \quad (4)$$

where α is the fine structure constant, ρ is the ratio of the real to the imaginary parts of the hadronic scattering amplitude at $t = 0$, δ is Bethe's phase shift ($\delta = -(\ln |t| + \ln b + 0.577)\frac{\alpha}{\beta}$), and b is the nuclear slope parameter.

The electromagnetic amplitudes are written in one-photon exchange approximation, keeping the leading terms only at high energy and small momentum transfer $|t|$, ($s \gg m^2 \gg |t|$),

$$\phi_1^e = \phi_3^e \approx \frac{\alpha\sqrt{s}}{t}, \quad (5)$$

$$\phi_2^e = -\phi_4^e \approx \frac{\alpha\sqrt{s}}{4m^2} (\mu - 1)^2 \quad (\mu = 2.79), \quad (6)$$

$$\phi_5^e = -\frac{\alpha\sqrt{s}}{|t|^{1/2}} \frac{\mu - 1}{2m}. \quad (7)$$

The contribution of the different components to the total asymmetry is written as,

$$A_N \frac{d\sigma}{dt} = \left(A_N \frac{d\sigma}{dt} \right)^e + \left(A_N \frac{d\sigma}{dt} \right)^h + \left(A_N \frac{d\sigma}{dt} \right)^i. \quad (8)$$

In Eq. (3) the interference term originates from the nuclear non-flip amplitude and the Coulombic charge-charge interaction. In Eq. (8), however, the interference comes from the nuclear non-flip amplitude and the charge-magnetic moment

interaction which gives an electromagnetic spin-flip amplitude. The major contribution to the asymmetry comes from the interference of ϕ_1^h and ϕ_3^h (non-flip) with ϕ_5^e (single-flip) amplitudes. The imaginary part of the hadronic amplitudes, ϕ_1^h and ϕ_3^h , can be calculated by the optical theorem, using the total cross section σ_{tot} .

$$Im(\phi_1^h + \phi_3^h) = \frac{1}{4\pi} [s(s - 4m^2)]^{1/2} \sigma_{tot} \quad (9)$$

where s is the center-of-mass energy squared and m is the proton mass.

Assuming zero electromagnetic A_N^e (single-photon exchange), the asymmetry in the Coulomb-nuclear interference region is written as [2],

$$A_N(t) = A_N^h(t) \frac{1}{1 + (\frac{d\sigma}{dt} / \frac{d\sigma^h}{dt})} + A_N^i(t), \quad (10)$$

$$A_N^i(t) = A_N^i(t_p) \frac{4z^{3/2}}{3z^2 + 1}, \quad (11)$$

where $z = t/t_p$ and $t_p = \sqrt{3}(8\pi\alpha/\sigma_{tot}) \approx 3.12 \times 10^{-3}(\text{GeV}/c)^2$. The maximum interference asymmetry is

$$A_N^i(t_p) \approx \frac{\sqrt{3}}{4}(\mu - 1) \frac{\sqrt{t_p}}{m} \approx 0.046, \quad (12)$$

where μ is the total magnetic moment of proton and m is the proton's mass. $A_N^h(t)$ at small $|t|$ values, on the other hand, appears to behave like [8]

$$A_N^h(t) \approx \sqrt{\frac{t}{s}} \quad (13)$$

and, accordingly, the interference term should dominate for $|t| \leq 6 \times 10^{-3}(\text{GeV}/c)^2$ at energies higher than 50 GeV.

Previous measurements with polarized targets could not access such a small $-t$ region because the recoil would be reabsorbed in the target, thereby making the kinematical determination of elastic-scattering events on the polarized free protons in the target impossible. By making use of a polarized beam and a recoil sensitive scintillator target we were able to observe polarization effects in the CNI region for the first time at high energies.

It should be noted that in the past high resolution forward spectrometers [9,10] and/or gaseous targets with recoil detection [11] were employed for the measurements in the CNI region at high energies with an unpolarized beam and target; on the other hand, for colliding beams the experimental problem is the detection of the scattered particles very close to the circulating beam [12,13].

Figure 1 shows (a) the differential cross-section measurement at 200 GeV/c [9], and (b) the theoretical prediction for the CNI analyzing power, A_N as a function of the four-momentum transfer squared [2]. Although the maximum polarization is only $\sim 4.6\%$, the average integrated cross section for $0.004 \leq t \leq 0.04 \text{ (GeV/c)}^2$ is relatively large, ~ 3.10 mbarns. This makes such an interference measurement possible and also suitable for applications as a high energy polarimeter.

If, however, the hadronic spin-flip amplitude is other than zero, the asymmetry predictions change. This could be the case, for instance, if the proton wave-function contains a dynamically enhanced diquark thus resulting in a spin-flip term to appear [14]. The question of spin-flip contributions to diffraction scattering has often been debated in the literature based on previous polarization measurements at higher $-t$ values and at 100 – 300 GeV/c [15–18], that indicate a flattening of the asymmetry at high energies.

Experimental Setup

Figure 2 shows the experimental setup, including (a) the schematic layout of the polarized ($p/\bar{p}$) beam-line at Fermilab and (b) the top-view of the CNI apparatus. Polarized protons are produced in the parity-nonconserving decays of Λ hyperons. The incoming 800-GeV/c primary proton beam strikes a beryllium target and creates unpolarized lambdas. In the unpolarized Λ rest frame, the decay $\Lambda \rightarrow p + \pi^-$ occurs isotropically and the decay-proton polarization is 64% with the spin direction along the proton momentum (for details see [19]). The 200-GeV/c polarized protons strike the active targets after their spins are rotated from horizontal to vertical by spin-rotation magnets. Beam hodoscopes, beam chambers,

before and after the spin-rotation magnets, and a pair of multi-strip silicon detectors before the targets, track the incident beam. The scattered track, after the active targets, is detected by a series of MWPCs up to the analyzing magnet, which is located at $z = 15.04$ m. The track deflected by the analyzing magnet (BM-109) is measured by yet another set of MWPCs and a Gray-Code (GC) hodoscope ($z = 46.20$ m). In order to center the deflected beam in the middle of the GC hodoscope, the GC was mounted on a remote-controlled movable pedestal. The deflection from the undeflected beam axis was about 12.98 cm at the GC when the magnet was operating at 2500 amperes.

The multi-scintillator target (MST) ensemble consisted of 6 *trans*-stilbene crystals (diphenyl-ethylene, $C_{14}H_{12}$) which have good pulse-shape discrimination (PSD) characteristics, and each target element was viewed by a XP2020 photomultiplier tube (see Table I).

For scattering events on the H atoms of the scintillator, the energy of the recoil proton ranges from a few MeV up to 24 MeV and the range of the recoil proton goes as high as 7 mm in *trans*-stilbene. Since these protons recoil close to 90° with respect to the beam axis, the target dimensions are chosen to be 3–4 cm in diameter and only a few millimeters in thickness.

The targets were aligned on an optical bench with respect to the beam-line and oriented normally to the beam direction in order to minimize the amount of energy deposited by through-going (minimally ionizing) beam and scattered protons and to maximize the response to protons that recoil (heavily ionizing) at angles of about 90° . The difference in pulse amplitudes between the through-going and the recoil proton, which deposits all of its energy in the target, is the principal idea of the discrimination between the two cases. This constitutes the first selection criterium in the first level trigger. There are, however, practical difficulties associated with this idea. The energy distribution of the through-going particles obeys an asymmetric Landau distribution. This distribution has a long tail in the higher energy end; extending somewhat into the energy range where energy distribution of the recoil protons starts. In order to minimize this effect, and to provide a sharper criterium for triggering over threshold, we chose a scintillating target that

possesses PSD characteristics, i.e., the time dependence of luminescence depends on the ionization density and therefore on the energy of the particles. The slow recoil protons produce, in the MST *trans*-stilbene crystals, pulses that have on the average a longer duration than that of the through-going beam particles.

Figure 3 schematically represents the timing characteristics of a scintillating material with PSD properties. The total light output from the crystal can be parametrized as a sum of the fast and slow components, i.e.,

$$L(t) = L_f \exp(-t/\tau_f) + L_s \exp(-t/\tau_s). \quad (14)$$

τ_f and τ_s are the decay-time constants and, L_f and L_s are the fitted coefficients for the fast and slow components, respectively. The fast decay-time constant, τ_f , is measured to be 4–6 ns and the slow decay time constant is ~ 275 ns [20,21]. By selecting the fast and slow parts of the pulses from the *trans*-stilbene crystals with prompt and delayed gates set according to the decay times, a simple PSD trigger can be constructed.

The entire target ensemble was surrounded by 11 lead-scintillator sandwich veto counters to eliminate all scattering and production processes, except those close to the beam. The most effective veto counter was the forward one positioned normally to the beam direction, with a 4.7 cm hole in the middle of the counter, which was centered around the beam.

The momentum transfer $|t|$ from the incident particle to the scattered proton is measured by reconstructing the track of the scattered proton. The kinetic energy of the recoil proton can be expressed as $T = |t|/2m$. Thus, it is possible to make a correlation between the two experimental and independently determined quantities, i.e., the kinematically measured $|t|$ values and the pulse amplitude recorded for the same event. This criterion, in principle, provides a tool for carbon background suppression since $T_{\text{carbon}} \approx 1/12 T_{\text{hydrogen}}$ for the same scattering angle.

For this measurement, 42 planes of multi-wire proportional chambers and 2 orthogonal planes of multi-strip silicon detectors (MSD) were used. The MSDs (3 cm $\times$ 3 cm) had 100 micron strips and were located before the targets at $z = -171.8$ cm.

An analyzing magnet was used to analyze the momentum of the particles. It was centered around $z = 15.04$ m and operated at 2500 amperes during data-taking. The magnet gap is $24'' \times 21''$ in x and y directions, respectively. The magnetic field is effectively flat at 13.78 KGauss in the central region. The momentum kick is about ~ 0.4 GeV/c.

The Gray Code (GC) hodoscope consists of two identical arrays with vertical and horizontal scintillator strips, determining x - and y -coordinates of the transmitted particles, respectively. It is segmented into $2^5 = 32$ bins, each 5 mm wide. Each array is subdivided into *direct* and *inverse* sections, and each is viewed by a set of 5 PMTs (for details see [22]). Two counters (16 cm $\times$ 16 cm) are placed immediately before and after the hodoscope and are used in coincidence with the hodoscope elements.

Trigger

The trigger for the CNI polarimeter consists of two major parts. The first part generates a good target (GT*) signal by exploiting the PSD characteristics of the active *trans*-stilbene targets whenever there is a recoil candidate in one of the six targets. The second part, initiated by the GT* signal, checks the scattering and azimuthal angles of the event by using the GC and makes a decision based on the information loaded on memory logic units (MLUs).

Figure 4 shows the simplified scheme of the PSD part; the pulse is separated into fast (F) and slow (S) parts by means of linear gates and a trigger is generated whenever the ratio S/F exceeds a given threshold. It typically takes 185 ns to make a PSD decision. The total and the slow components of the pulses from each target crystal are read also by ADCs (130 ns gate width). If there is a good event, i.e., master trigger, the ADCs are read and cleared.

The MLU logic is designed such that it projects the undeflected beam track onto the GC and checks if the event meets the scattering requirements for the forward scattering angle θ_s and the azimuthal angle ϕ . MLUs are loaded with a *butterfly* cut (Fig. 5) to eliminate the up and down scattered particles and a 1.1 cm

$\times 1.1$ cm square is cut out in the center to eliminate the straight-through beam particles, thus accepting only particles that scatter left and right of the beam.

The diffuseness of the MLU cuts has an impact in the very low $-t$ region in terms of background. The events that scatter at very small angles are sensitive to the sharpness of the cuts. The border effects of the GC also contribute to this in a lesser degree since the inconsistent events are omitted by the coding of the hodoscope at the trigger level.

Data Analysis

There are two major parts to the apparatus of the Coulomb-nuclear interference measurement, i.e., the forward spectrometer and the active *trans*-stilbene targets. The correlation between the scattering angle measured by the forward spectrometer and the pulse amplitude from the recoil protons in the active *trans*-stilbene targets constitutes the primary criterion in separating the elastic *pp* events from a number of different backgrounds.

The reconstructed tracks determine four of the critical parameters of the measurement, i.e., vertex position, scattering angle θ_s , azimuthal angle ϕ and momentum of the scattered particle. In the off-line vertex analysis, the hodoscopes upstream of the target area and the GC are mainly used to define a road in which the tracks are reconstructed. This procedure saves significant time in computing. The reconstruction is done in three different stages; the incident track before the targets, the scattered track after the targets and the deflected track after the analyzing magnet. The track is reconstructed for each segment and at the intersection points (target and the analyzing magnet) the distance between the tracks is minimized. The maximum allowed distance is 2 millimeters in both x- and y-directions. At the target and at the analyzing magnet locations, the tracks are joined when the χ^2 values are acceptable.

The CNI trigger requires that the beam interacts only in one of the targets, and until the event is fully processed the data acquisition system is latched. In this way the reconstruction of the z-vertex distribution for each target is possible. All

the multiple-track events are also rejected. The standard deviation for the z-vertex distribution for individual targets range from 24.7 to 32.8 cm and the absolute value of the difference between the mean reconstructed z-vertex and the surveyed target position ranges from 0.1 to 4.5 cm (Table I).

The momentum measurement of the incident protons with the forward spectrometer and the spectrometer at the tagging region in the intermediate focus of the beam agree within a few per cent. The beam momentum spread is about $\pm 9\%$ and the mean momentum is 200 GeV/c.

The momentum spread of the beam is further dispersed by the analyzing magnet. This smears the distribution of events detected at GC, thereby directly effecting the low $-t$ cut in the trigger. Momentum correction for each event using the tagged beam momentum at the level of MLUs was employed in the trigger. On the other hand, the analyzing magnet reduces the background due to low-energy charged particles at the level of the trigger.

The fractional accuracy of the analyzing magnet is given by

$$\frac{\Delta p}{p} = 0.003 \frac{p \Delta \theta_B}{BL} \quad (15)$$

and it is estimated to be about 1%. The momentum p is 200 GeV/c, the accuracy of the bending angle $\Delta \theta_B$ is about 0.042 milliradians and BL is 2.52 Tesla meters.

Selection of pp Elastic Events

The correlation between the four-momentum transfer squared $|t|$ (or the forward scattering angle θ_*) and the ADC counts of pulse amplitudes is used in identifying the elastic events. The elastic events present themselves as a distinct diagonal band on the $|t|$ vs. ADC scatter plot. Scattering from the carbon nuclei and the straight-through events are observed as a horizontal band. Figure 6 shows this correlation between $|t|$ and the slow component of the ADC for target 1.

There are processes other than elastic pp scattering that take place when a proton strikes a target. Scattering from the carbon nuclei constitutes one of the sources of background. Straight-through particles also obscure the elastic pp events, especially in the lowest $|t|$ -region. In addition, a broad distribution of quasi-elastic

events contributes to the background. In order to extract the pure pp elastic events from the background, three different criteria are applied to the data set.

1. A priori, two parallel diagonal cuts, above and below the elastic-event band, are applied to eliminate most of the uncorrelated and quasi-elastic events.
2. A Z-vertex cut, $|Z_{reconstructed} - Z_{surveyed}| \tan \theta_s < M\sigma$, where $1.65 \leq M \leq 2.2$ and σ is the standard deviation of the $(Z_{reconstructed} - Z_{surveyed}) \tan \theta_s$ distribution, constrains the events that come from a given target.
3. Much like the case above, another constraint is constructed for the four-momentum transfer squared. If $|t_{measured} - t_{expected}| > \Delta$, where $0.009 (\text{GeV}/c)^2 \leq \Delta \leq 0.01 (\text{GeV}/c)^2$, then the event is rejected. $t_{expected}$ is deduced from the recoil energy as described below.

The ADC (slow component) counts vs. $-t$ for target 1 are shown in Fig. 6b after the z-vertex cut is applied. In general, the background events are seen only in the lowest ADC channels. These events are mostly due to carbon scattering, minimally-ionizing through-going beam particles with large multiple scattering and uncorrelated particles that are accepted by the trigger.

If one makes a binning of the $|t|$ vs. ADC correlation, in equal $|t|$ intervals ($\Delta t = 0.0025 (\text{GeV}/c)^2$), the projection of the events onto the ADC axis exhibits the distributions that are obeyed by each specific type of event (see Fig. 7). The through-going particles show a Landau-tail distribution cut at the low side by our trigger threshold, whereas the pp recoil events obey gaussian statistics. The sum of the asymmetric tail of the Landau distribution and a free varying Gaussian distribution for the elastic pp events is fitted to the ADC spectra. The most probable energy and the mean energy deposition of through-going protons are calculated from the Bethe-Bloch equation and used to fix the Landau distribution in energy. The most probable energy-loss for the targets of different thickness ranges between 0.3 and 0.9 MeV, whereas the mean energy-loss ranges from 0.6 to 1.8 MeV [23]. As $|t|$ values increase, the gaussian distribution separates from the background events, enabling us to make a correlation between the $|t|$ values and expected ADC counts per hit.

The central peaks of the gaussian distribution, in the relatively background-free momentum-transfer region, can be linearly fitted to form a correlation between the expected $|t|$ and ADC values. Based upon this criterion, it is possible to further restrict the $|t|$ vs. ADC correlation. From this linear fit, t_{expected} values are calculated for each measured ADC count. The first few bins are omitted from the fit so as not to produce bias by the events that are at the very low $-t$ region which is most contaminated by background. Consequently, comparison of the expected and the measured $-t$ values is possible. As mentioned earlier, this criterion is used to constrain the $-t$ distribution further, in particular at low $-t$.

The quasi-elastic scattering and recoil protons that escape from the targets present a broader spectrum of lower level background in a larger $|t|$ range. The inelastic events are principally vetoed by the target veto counters that surround the target assembly.

The factors that determine the precision of the forward spectrometer are the multiple scattering of the forward particles, the measurement accuracy of the wire chambers and the uniformity (momentum kick) of the analyzing magnet.

The multiple-scattering effects are due to the elastic Coulomb interactions of the forward particles with the material in the beam. This can be calculated as follows,

$$\Delta\theta_{ms} = \frac{14.1}{p} \sqrt{L/L_R} (1 + 1/9 \log_{10} L/L_R) \quad (16)$$

where p is the particle momentum in GeV/c and $\Delta\theta_{ms}$ is in milliradians. L is the length of the material in the beam and L_R is the radiation length of the material. Since in Coulomb-nuclear interference the angles of scattering are in the order of fractions of milliradians, it is important to minimize the mass in the beam. We had He bags between detector elements to minimize multiple scattering. The total amount of material in the beam for our measurement resulted in $\Delta\theta_{ms} \approx 0.021$ milliradians.

The measurement error can be estimated from the position resolution of the MWPC, $\sigma = 0.289S$ where S is MWPC wire spacing in mm. The measurement error is about 0.033 milliradians for our geometrical setup.

The multiple scattering of the events from the material in the beam contribute to the overall broadening of the $-t$ distribution. The average scattering angle for the first $-t$ bin is about 0.33 milliradians. Thus, this particular $-t$ bin is more sensitive to the multiple scattering of the events. We applied a tighter cut in the z -vertex in order to reject through-going particles more effectively, which could dilute the observed asymmetry in the lowest $-t$ bin.

Calculation of Asymmetries

In extracting the analyzing power A_N from the measured count rates there are several ways of calculating the *raw* asymmetries ϵ as a function of the various parameters defining the scattering event and the beam spin state:

1. Left-Right scattering: The apparatus is (in principle) left-right symmetric with respect to the beam. The azimuthal angle ϕ is measured by the spectrometer. At the trigger level two regions are defined, ($L \equiv -\Phi < \phi < \Phi$ and $R \equiv \pi - \Phi < \phi < \pi + \Phi$), for all of the scattering angle θ_s accepted and $\Phi \approx \pi/4$.
2. Polarization tagging: The beam contains both positive and negative polarization states in seven bins $P_i = (i = 1, \dots, 7)$ from -65% to $+65\%$. Omitting the central bin, $i = 4$ (average zero polarization state, $\langle P_4 \rangle = 0$) used for control purposes only, we define negative $P < 0, (i = 1, 2, 3)$ and positive $P > 0, (i = 5, 6, 7)$ polarization states of the beam.
3. Snake magnet state: Snake magnets reverse the spin direction every 10 spills (~ 6 times per hour). This reversal of spin direction is used to eliminate the systematic errors. The state of the snake system is labelled according to the orientation of the polarization state from tagging at the target.

For each $|t|$ bin, the number of events as a function of the above three parameters is defined as $N = N(L/R, +/ -, \uparrow / \downarrow) = (\text{Left/Right, polarization state, snake state})$.

For example:

$$N(L, +, \uparrow) = N(+, \uparrow)\alpha(L) \int_{-\Phi}^{\Phi} d\phi \int_{\theta-\delta\theta/2}^{\theta+\delta\theta/2} \frac{d\sigma}{d\Omega} \sin\theta d\theta (1 + A_N(\theta)P_+ \cos\phi), \quad (17)$$

$$N(R, -, \uparrow) = N(-, \uparrow)\alpha(R) \int_{-\Phi}^{\Phi} d\phi \int_{\theta-\delta\theta/2}^{\theta+\delta\theta/2} \frac{d\sigma}{d\Omega} \sin\theta d\theta (1 + A_N(\theta)P_- \cos\phi), \quad (18)$$

$$N(L, -, \downarrow) = N(-, \downarrow)\alpha(L) \int_{-\Phi}^{\Phi} d\phi \int_{\theta-\delta\theta/2}^{\theta+\delta\theta/2} \frac{d\sigma}{d\Omega} \sin\theta d\theta (1 + A_N(\theta)P_- \cos\phi), \quad (19)$$

$$N(R, +, \downarrow) = N(+, \downarrow)\alpha(R) \int_{-\Phi}^{\Phi} d\phi \int_{\theta-\delta\theta/2}^{\theta+\delta\theta/2} \frac{d\sigma}{d\Omega} \sin\theta d\theta (1 + A_N(\theta)P_+ \cos\phi). \quad (20)$$

The azimuthal angle ϕ is integrated between the maximum and the minimum of the ϕ acceptance (see Fig. 5). $N(+, \uparrow)$, etc. refer to the beam flux for each (tagging and snake) state and $\alpha(L)$, etc. represents the weighting factor for the left scattering (including efficiencies and acceptances) for the considered $|t|$ bin. The other four states are expressed in a similar way with a negative sign in front of A_N .

We define the following rates in the left and right regions according to the polarization state at the target:

$$L^+ = [N(L, +, \uparrow)N(L, -, \downarrow)]^{1/2} \quad \text{and} \quad R^- = [N(R, +, \downarrow)N(R, -, \uparrow)]^{1/2} \quad (21)$$

$$R^+ = [N(R, +, \uparrow)N(R, -, \downarrow)]^{1/2} \quad \text{and} \quad L^- = [N(L, +, \downarrow)N(L, -, \uparrow)]^{1/2} \quad (22)$$

By using the geometrical mean, all the normalization coefficients are factored out and are automatically cancelled when the asymmetry is calculated as

$$\begin{aligned} \epsilon &= \frac{\sqrt{L^+ R^-} - \sqrt{L^- R^+}}{\sqrt{L^+ R^-} + \sqrt{L^- R^+}} \\ &= \frac{N(+, \uparrow)P_+ + N(-, \downarrow)P_-}{N(+, \uparrow) + N(-, \downarrow)} \left(\frac{\sin\Phi}{\Phi} \right) \frac{\int A_N(\theta) \frac{d\sigma}{d\Omega} \sin\theta d\theta}{\int \frac{d\sigma}{d\Omega} \sin\theta d\theta}. \end{aligned} \quad (23)$$

The value of A_N in the $|t|$ bin considered is therefore

$$A_N(t) = \frac{\Phi}{\sin\Phi} \frac{\epsilon}{P_{beam}}. \quad (24)$$

The approximate statistical error can be estimated as;

$$\Delta\epsilon \approx \frac{1 - \epsilon^2}{\sqrt{N_{tot}}}. \quad (25)$$

The systematic effects are estimated by considering $\epsilon(\langle P_{beam} \rangle = 0)$, using the central bin of the tagging states (Table II) and by the *fake* asymmetries. Therefore, six other asymmetries are calculated as a measure of control of the apparatus and a double-check of the results. These are $\epsilon_{L/R}$, $\epsilon_{\uparrow/\downarrow}$ and $\epsilon_{+/-}$. They are defined as;

$$\epsilon_{L/R} = \frac{\sqrt{N(L/R, +, \uparrow)N(L/R, -, \downarrow)} - \sqrt{N(L/R, +, \downarrow)N(L/R, -, \uparrow)}}{\sqrt{N(L/R, +, \uparrow)N(L/R, -, \downarrow)} + \sqrt{N(L/R, +, \downarrow)N(L/R, -, \uparrow)}}, \quad (26)$$

$$\epsilon_{\uparrow/\downarrow} = \frac{\sqrt{N(L, +, \uparrow/\downarrow)N(R, -, \uparrow/\downarrow)} - \sqrt{N(L, -, \uparrow/\downarrow)N(R, +, \uparrow/\downarrow)}}{\sqrt{N(L, +, \uparrow/\downarrow)N(R, -, \uparrow/\downarrow)} + \sqrt{N(L, -, \uparrow/\downarrow)N(R, +, \uparrow/\downarrow)}}, \quad (27)$$

$$\epsilon_{+/-} = \frac{\sqrt{N(L, +/-, \uparrow)N(R, +/-, \downarrow)} - \sqrt{N(L, +/-, \downarrow)N(R, +/-, \uparrow)}}{\sqrt{N(L, +/-, \uparrow)N(R, +/-, \downarrow)} + \sqrt{N(L, +/-, \downarrow)N(R, +/-, \uparrow)}}. \quad (28)$$

The six raw asymmetries that are described above are used as a check of the systematic errors. The differences $\Delta\epsilon_{LR} = \epsilon_L - \epsilon_R$ (*space* asymmetry), $\Delta\epsilon_{\uparrow\downarrow} = \epsilon_{\uparrow} - \epsilon_{\downarrow}$ (*snake* asymmetry) and $\Delta\epsilon_{+-} = \epsilon_{+} - \epsilon_{-}$ (*tagging* asymmetry) should all be consistent with zero.

Results and Discussions

The analyzing power A_N in pp elastic scattering was measured using the 200-GeV/c polarized proton beam facility at the Fermi National Accelerator Laboratory (FNAL) for the first time in the Coulomb-nuclear region. The effective four-momentum transfer squared ranged from $1.5 \times 10^{-3} (\text{GeV}/c)^2$ to $5.0 \times 10^{-2} (\text{GeV}/c)^2$. The results are summarized in Table II, and Fig. 8 presents both the results and our earlier preliminary measurement at 185 GeV/c [24]. The asymmetry expected for pure interference of ϕ_5^e and $(\phi_1 + \phi_3)^h$ in pp scattering is represented with the solid line in Fig. 8. The errors shown in Table II are statistical only.

For $-t > 0.004 (\text{GeV}/c)^2$, the background events, mainly from pC scattering and non-interacting beam particles, were successfully rejected by our trigger; for

$-t \leq 0.004(\text{GeV}/c)^2$, however, the error bar is large due to restrictive cuts to eliminate much of the background. We expect that non-interacting particles might dilute the measured asymmetry, but for pC scattering the analyzing power should be comparable to that of pp [25].

In order to verify that systematic uncertainties do not effect the asymmetry measurement, we give the measured raw asymmetry parameter $\epsilon(\langle P_b \rangle = 0)$ with the average-zero polarization part of the beam in Table II and in Table III we present the three *fake* asymmetry parameters as discussed in the previous section; $\Delta\epsilon_{LR}$, $\Delta\epsilon_{\uparrow\downarrow}$ and $\Delta\epsilon_{+-}$. They are all consistent with zero within statistical uncertainty.

For the sake of completeness, we include in Fig. 8 the polarization asymmetry results of previous pp elastic-scattering measurements performed at moderately low $-t$ values ($0.15 < -t < 0.3(\text{GeV}/c)^2$) at 100–300 GeV/c beam momenta [15–18]. They all used polarized targets as opposed to a polarized beam, as in our case. When these and other lower energy experiments [27,28] are considered together over the full $-t$ range, they show the following general features for the asymmetry in pp elastic scattering at high energy:

- a positive analyzing power A_N at small $-t$ values ($-t < 0.3(\text{GeV}/c)^2$), decreasing with increasing s up to $s \approx 50(\text{GeV})^2$, with possible flattening around values of a few per cent up to the highest energies,
- for $s > 50(\text{GeV})^2$, A_N changes sign in the $-t$ range between 0.4 and 1.0 $(\text{GeV}/c)^2$ and remains negative in the region where the diffractive dip in the differential cross-section develops around $-t \approx 1.2(\text{GeV}/c)^2$.

These features have stimulated a number of speculations on a possible hadronic spin-flip contribution ϕ_5^h that does not necessarily decrease as $\sqrt{s}$. It was suggested that diffractive scattering with exchange of two pions could become important at large s ; this mechanism can cause a non-vanishing ϕ_5^h because one of the two pions can couple with spin-flip, while the other does not. More recently, it was pointed out that ϕ_5^h might remain non-zero at high energies if the nucleon contains a dynamically enhanced component with a compact diquark [14]. In the first case, the ratio of $\phi_5'^h$ (the reduced spin-flip amplitude corresponding to ϕ_5^h without the kinematical

factor $\sqrt{t}$) and $(\phi_1 + \phi_3)^h$ can be as high as 0.25; in the second case, the effect is expected to be 0.05–0.1.

An attempt has been made to extract the behaviour of $\phi_5'^h$ from cross section and polarization data and the result is $\phi_5'^h$ might be comparable to $(\phi_1 + \phi_3)^h$ at $-t = 0$ [26]. It should be noted, however, that the observed polarization is dominated by the kinematical terms at relatively small $-t$ values and the data available at that time were limited to $|t| \geq 0.15(\text{GeV}/c)^2$.

The results presented here agree well with the theoretical prediction of a purely CNI asymmetry originating from the interference of ϕ_5^e and $(\phi_1 + \phi_3)^h$ in the $-t$ range of 10^{-3} to $10^{-2}(\text{GeV}/c)^2$. Within experimental accuracy, the results do not discount the possibility of a non-zero spin-flip hadronic amplitude at the level of a few per cent of the dominating non-flip one. There is no measurement of analyzing power to this day in the range of $0.05 \leq -t \leq 0.15(\text{GeV}/c)^2$. In view of the renewed interest in the high energy behaviour of elastic scattering and the debated structure of the pomeron, it might be of significant interest to extend these types of measurements with high precision to the range of $0.001 \leq -t \leq 0.2(\text{GeV}/c)^2$.

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TABLE I. Dimensions and surveyed^a and reconstructed^b positions for each target along the beam-line. The mean z-vertex position the standard deviation values are gaussian-fitted values.

Target No.	Thickness [mm]	Z-vertex ^a [cm]	Z-vertex ^b [cm]	σ [cm]
1	2.0	-60.1	-59.5	24.7
2	2.0	-20.1	-15.6	32.0
3	3.0	19.9	21.5	32.8
4	3.0	39.9	41.5	28.8
5	5.0	59.9	60.0	30.6
6	6.2	79.9	79.9	28.8

TABLE II. Results of the CNI measurement. The last column is the raw asymmetry measured with the part of the beam where the average beam polarization is zero.

$-t$ Range (GeV/c) ²	$< -t >$ (GeV/c) ²	N Events	A_N [%]	Raw Asym. $< P_b > = 0$ [%]
$1.50 \times 10^{-3} - 4.00 \times 10^{-3}$	2.88×10^{-3}	5695	4.46 ± 3.16	-1.22 ± 1.51
$4.00 \times 10^{-3} - 1.25 \times 10^{-2}$	8.30×10^{-3}	47223	3.11 ± 1.09	0.11 ± 0.58
$1.25 \times 10^{-2} - 2.25 \times 10^{-2}$	1.75×10^{-2}	55473	2.62 ± 1.01	1.23 ± 0.52
$2.25 \times 10^{-2} - 3.25 \times 10^{-2}$	2.73×10^{-2}	49386	3.17 ± 1.07	-0.35 ± 0.57
$3.25 \times 10^{-2} - 4.25 \times 10^{-2}$	3.68×10^{-2}	29872	2.17 ± 1.39	-0.21 ± 0.61
$4.25 \times 10^{-2} - 5.00 \times 10^{-2}$	4.75×10^{-2}	9563	0.27 ± 2.77	0.35 ± 1.29

TABLE III. The raw control asymmetries (*space*, *snake* and *tagging*) for the CNI measurement. All the errors are statistical.

$-t$ Range (GeV/c) ²	$\Delta\epsilon_{LR}$ [%]	$\Delta\epsilon_{ }$ [%]	$\Delta\epsilon_{+-}$ [%]
$1.50 \times 10^{-3} - 4.00 \times 10^{-3}$	-3.74 ± 2.66	-0.45 ± 2.66	-2.12 ± 2.66
$4.00 \times 10^{-3} - 1.25 \times 10^{-2}$	-1.04 ± 0.92	1.11 ± 0.92	-1.88 ± 0.92
$1.25 \times 10^{-2} - 2.25 \times 10^{-2}$	0.64 ± 0.85	1.34 ± 0.85	-0.39 ± 0.85
$2.25 \times 10^{-2} - 3.25 \times 10^{-2}$	-0.44 ± 0.90	0.24 ± 0.90	-2.19 ± 0.90
$3.25 \times 10^{-2} - 4.25 \times 10^{-2}$	1.75 ± 1.17	1.39 ± 1.17	-0.05 ± 1.17
$4.25 \times 10^{-2} - 5.00 \times 10^{-2}$	0.49 ± 2.33	-0.82 ± 2.33	4.15 ± 2.33

FIG. 1. (a) The $pp \rightarrow pp$ differential cross-section measurement at $200 \text{ GeV}/c$ [9] and (b) proton analyzing power as a function of $-t$ for the CNI process. The $|t|$ dependence of the differential cross section and the ratio of imaginary to real parts of the forward amplitudes ρ are neglected.

FIG. 2a. The side view of the secondary beam-line elements. The secondary beam-line consists of production target, neutral particle dump, adjustable collimator, beam tagging region and Cherenkov counters before the spin rotating magnets and the experimental target(s). For more details see [19].

FIG. 2b. Top-view layout of the CNI polarimeter. The dimensions transverse to the beam are not to scale.

FIG. 3. PSD characteristics of *trans*-stilbene. The recoil particles generate a pulse with longer tails compared to the minimally-ionizing particles. By choosing appropriate gates, this characteristic of the crystal is exploited to distinguish recoils from beam particles.

U 690 330

FIG. 4. Simplified PSD trigger used in this measurement. The times of propagation of signals in nanoseconds are indicated by the numbers in circles.

FIG. 5. The *butterfly* cut as observed at GC. The events in the central part (beam), upper and lower quadrants are rejected at the trigger level.

FIG. 6a. The correlation between the four-momentum transfer squared $-t$ and the ADC slow component for target 1. The x-axis represents the ADC counts; y-axis is the four-momentum transfer squared in $(\text{GeV}/c)^2$; and the z-axis represents the number of events. Plots shown are before the elastic pp event selection as described in Section IV.A. The diagonal band of events is due to elastic pp scattering. The background is observed as the high horizontal band.

FIG. 6b. Plots shown are after the z-vertex cut as described in Section IV.A. The diagonal band of events is due to elastic pp scattering. The background is observed as the high horizontal band.

FIG. 7. The projection of slow component ADC values as a function of $-t$ bins where each plot corresponds to $\Delta t = 0.0025 \text{ (GeV/c)}^2$. In the case of lower t -range the background is dominant and described by a Landau distribution and as the $-t$ values increase the elastic pp events separate from the background and exhibit a gaussian distribution. The plots represent the ADC spectra for the $-t$ bins of (a) $0.0075 \leq -t \leq 0.0100 \text{ (GeV/c)}^2$; (b) $0.0125 \leq -t \leq 0.0150 \text{ (GeV/c)}^2$; (c) $0.0175 \leq -t \leq 0.0200 \text{ (GeV/c)}^2$; (d) $0.0225 \leq -t \leq 0.0250 \text{ (GeV/c)}^2$; and (e) shows the scaling of the mean of the pp elastic peak with the four-momentum transfer squared.

FIG. 8. A_N data for pp elastic scattering as a function of $-t$. The solid curve is the theoretical prediction [2] in the Coulomb-nuclear interference region. $\circ$ is measured at 185 GeV/c [24] and the results of this measurement are indicated by $\bullet$. The other data points are measured at 300 GeV/c (cross) and 100 GeV/c (diamond) [16], 176 ± 12 GeV/c (triangle) [17], and at 150 GeV/c (black square) [15], using a polarized target.

Inclusive Λ Measurements

Our second main activity was the study of $p \uparrow p \rightarrow (\pi^\pm, \Lambda, \Sigma^0) + X$ reaction. At present we are trying to tune the reconstruction program to achieve a higher reconstruction efficiency. We hope to produce the final results for this channel during FY94. This channel will be the Ph.D. thesis subject for Sandro Bravar. Figure 9 shows the Iowa-Trieste Forward Spectrometer for E-704. Figure 10 shows the E-704 experimental phase space for $pp \rightarrow \Lambda x$ from our data. Figure 11 shows the selected Λ invariant mass distribution.

Forward Spectrometer

FNAL E-704

LH2 — 1 meter liquid hydrogen

PC's — Multiwire prop. chamber planes

MP9AN — Analyzing Magnet 1.4 Tesla

H's — Trigger Hodoscope Panels

CI — Threshold $\bar{C}$ counter, 25 m long

DCI — Drift Chamber

FIG. 9

Λ^0 KINEMATICAL RANGE FOR E-704

FIG. 10

FIG. 11. Proton-pion invariant mass after selection cuts.

E-683

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E-683 is the photoproduction of high $p_{\perp}$ hadronic jets experiment (Y. Onel, Deputy Spokesman). Hadronic jets are formed when a quark is torn from a nucleon. Therefore, as the quark travels outward from the nucleus, quark-antiquark pairs form near it, and these pairs travel in the general direction of the original quark, thus forming a jet. This process is called hadronization. Due to the fact that our beam is composed of photons whose energy spectrum is the highest available, E-683 is in a unique position to conduct a number of cross-section measurements. Such processes include $\gamma + q \rightarrow 4$ jets, $\gamma + q \rightarrow gq$ (QCD Compton), $\gamma + q \rightarrow q\bar{q}$ (quark-gluon fusion), and nuclear-dependent studies.

In the $\gamma + p \rightarrow 4$ jets process, we see in Fig. 1 that the photon dissociates into a $q\bar{q}$ pair, and one of the pair emits a gluon that couples with one of the quarks in the nucleon. There are four jets produced by this event: a beam jet, a target jet, and two high $p_{\perp}$ jets. The types of interactions that are involved in calculations concerning this process are $qq \rightarrow qq$ and $qg \rightarrow qg$. The interaction $qg \rightarrow qg$ dominates the $\gamma + p \rightarrow X$ interaction for $p_{\perp} \leq 4$ GeV.

The next three reactions involve only three jets: due to the point-like coupling of the phenomena, there are no beam jets. Since these three processes are the only three-jet processes possible, E-683 is in an excellent position to measure the cross sections for these processes. In the process $\gamma + q \rightarrow gq$ (QCD Compton), the photon couples directly with a quark, which then emits a gluon as it leaves the nucleus (see Fig. 2). QCD Compton dominates the entire $\gamma + p \rightarrow \text{jet} + X$ process for $p_{\perp} \geq 4.5$ GeV, comprising $\geq 80\%$ of the cross section for $p_{\perp} \geq 6$ GeV.

In photon-gluon fusion, as seen in Fig. 3, the photon dissociates into a $q\bar{q}$ pair. One of the quarks then couples to a gluon in the nucleon, producing two high $p_{\perp}$ jets. The spectator quarks in the target form a third jet.

In γ -N collisions, both three-jet and four-jet processes should have $\sigma \propto A^1$ behavior, since hadronization occurs outside the nucleus. However, jet production in hadron beams exhibits a $\sigma \propto A^{\alpha}$ dependence, where $\alpha > 1$. Therefore, in E-683, we expect $\sigma \propto A$, since hadronization occurs outside the nucleus. However, in the higher-twist process, the cross section could be affected by a process known as "color-transparency."

In higher-twist production of pions, the photon couples to a quark from the target (see Fig. 4). The quark then emits a hard gluon which splits into a $q\bar{q}$ pair. The $q\bar{q}$ form a single π , at high $p_{\perp}$, balanced by a quark jet. In the conventional view of the process, the π will not exit from a large nucleus, since the quarks in the larger nucleus will eventually interact with one of the quarks of the pion. However, in the "color-transparency" theory, the π will exit the nucleus because production of a composite particle at a high $p_{\perp}$ uses a spatially small section of its wave function. Then the radius of the π is small, and therefore not observed by other quarks in the nucleus. Measurements of the A-dependence of higher-twist π would be a test of color transparency. Since the existence of the higher-twist process can be established independently in the process $\gamma + p \rightarrow \pi + X$, E-683 is in a unique position to test color transparency.

The Wide Band Beam at Fermilab provides the world's highest energy tagged photon beam. The large-solid-angle coverage of our calorimeters, including full coverage in the forward direction, provides us with a unique opportunity to study the direct-coupling of the photon to partons in the target nucleons. The first-order QCD processes of interest are the QCD Compton and photon-gluon fusion diagrams. In some cases, the photon first dissociates into a quark-antiquark pair before it interacts. Events of this type will allow us to obtain new information on the photon structure function. Complete second-order calculations have been done by Jeff Owens of Florida State, who has helped us a great deal in understanding and applying his work.

In addition to studying jet photoproduction with a hydrogen target, the A-dependence of jet photoproduction will be studied in detail. We have taken data with a liquid deuterium target and six solid nuclear targets ranging from Be to Pb. We know from our previous experiment E-609 that large A-dependent effects are seen in jet production in p-A interactions. The presence of the nucleus greatly decreases the energy flow in the forward direction; the energy loss is consistent with an $A^{1/3}$ dependence. In addition, we see strong evidence for a significant amount of multiple-scattering of the partons as they exit the nucleus, producing an additional

p_t unbalance or E-683 k_t of 1 GeV for p-Pb interactions. Our data are consistent with the hadronization process occurring outside the nucleus.

The origin of such large A-dependent effects is not well understood. Multiple-scattering models qualitatively produce the type of effects that were observed in E-609, but in general the effects they predict are too small. Most multiple-scattering models would also predict substantial A-dependent effects in Drell-Yan production, since one would expect the incoming hadron to also undergo multiple scattering. But the Drell-Yan data indicate that any A-dependent effects are small. Sivers has suggested that our results may be due to a final-state interaction between the outgoing partons.

Data from E-683 as well as other recently-completed Fermilab experiments should shed light on the question. E-706 has data on the A-dependence of direct photon production in a hadron beam; the final state in this case is one parton and one photon. And E-665 has data on the A-dependence of deep inelastic muon scattering, in which the final state is one parton and one muon. Information from all these experiments together gives us a real opportunity to learn about the passage of colored objects through nuclear matter.

Current Status

Radiation shielding problems in both the external beam lines and in the accelerator itself delayed the start of the fixed-target run until late June of 1991. After the start-up period, the accelerator ran fairly reliably, with the run lasting about six months. The fixed-target run ended February 1992.

We took data with a hydrogen target, a deuterium target, and six solid nuclear targets. Below is a summary of the raw triggers and estimated dijet samples for each of these targets. The nuclear target data is split roughly evenly between the six targets, which were Be, C, Al, Cu, Sn, and Pb.

Preliminary Results

Jets arise from the fragmentation of partons in hard scattering processes. Jets have been observed in many experiments in hadron-hadron interactions [1] as well as in deep inelastic lepton-hadron interactions [2] and e^+e^- annihilations [3]. Single high p_t hadrons and energy flow distributions have been studied in earlier, lower energy, photoproduction experiments [4], but until now no observation has been made of jet production by a real photon beam. Recent results from HERA show evidence for hard scattering in almost-real photon-proton interactions [5]. In this letter we report the first observation of jets produced by a real photon beam incident on a proton target.

In low momentum-transfer processes, photon interactions leading to hadronic final states can be described by the vector-dominance model (VDM), in which photons act like vector mesons [6]. But at high momentum transfer (high p_t), other processes are expected to dominate [7]. These include the direct coupling contribution, in which the photon couples directly into the hard scattering process, and the so-called "resolved" or "anomalous" photon contributions, in which the photon first dissociates into a quark-antiquark pair before interacting. In the direct coupling process, the photon completely disappears, leaving no spectator remnant. The final state consists of three jets: two high- p_t jets and a soft target jet. In both the VDM and "resolved" contributions, the photon has a spectator remnant, thus producing a four-jet final state. In the p_t range of this experiment, VDM processes are not expected to contribute appreciably, while the direct and resolved contributions are expected to compete [8]. When higher-order QCD diagrams are considered, there is no sharp distinction between the direct and resolved processes, but with well-defined experimental cuts, it might be possible to divide events into categories which approximate the Born-level contributions, and quantitative comparisons between data and theory can then be made.

We have observed the photoproduction of high p_t jets in experiment E-683 in the Wide Band photon beam at Fermilab which is the world's highest energy tagged photon beam. Jets have been observed with single jet p_t 's in the range 3 GeV/c to 9 GeV/c. Incident tagged photon energies ranged from 50 to 400 GeV. Photons

were produced by bremsstrahlung from a secondary electron beam incident on a lead radiator which was 20% of a radiation length. The incoming electron beam had a mean momentum of 310 GeV/c and an rms momentum spread of $\pm 15\%$. The energy of the incoming electrons was tagged by an array of silicon microstrip detectors upstream, between, and downstream of a pair of dipole magnets. Two planes of scintillation counters near the silicon detectors monitored beam flux and occupancy of nearby beam buckets. After the electron radiated, sweeper magnets bent it into an array of shower counters which measured the electron's final energy. The photon energy (excluding effects of multiple bremsstrahlung) is the difference between the incoming and outgoing electron energies, and is known to $\pm 5\%$. Monte Carlo simulations of the beam indicate that multiple bremsstrahlung in the radiator leads to less than a 5% overestimate of the photon energy. We have not attempted to correct the photon energy for multiple bremsstrahlung, since it is not an important effect in this analysis.

The experimental apparatus is shown in Fig. 5. Two scintillation counters upstream of the hydrogen target vetoed charged particles from photons which had converted in material upstream. A counter immediately downstream of the target required at least one charged track exiting the target. Two planes of scintillator hodoscopes vetoed events which were accompanied by a muon. Downstream of the target were five planes of multiwire proportional chambers and six planes of drift chambers, followed by an analysis magnet and an additional 13 planes of drift chambers. The magnet had a small p_t kick (about 100 MeV/c) so as not to interfere with calorimeter-based jetfinding.

After the wire chambers was a highly segmented electromagnetic and hadronic main calorimeter (MCAL), covering a laboratory pseudorapidity (η) range from 2.6 to 4.9. The MCAL has been described in detail elsewhere [9]. It consisted of 132 towers of lead-scintillator and steel-scintillator sampling calorimetry, each tower being four layers deep. Each tower covered a $\Delta\eta$ and azimuthal ($\Delta\phi$) range of about 0.3. Measured energy resolutions were $\frac{\sigma}{E} = \frac{35\%}{\sqrt{E}}$ for electromagnetic particles and $\frac{85\%}{\sqrt{E}}$ for hadrons, where E is in GeV. The absolute energy scale of the calorimeter in this analysis is uncertain to about 7%.

A beam calorimeter (BCAL) downstream of the main calorimeter measured the energy flow in the forward direction. It covered η down to 4.9 in the laboratory frame, which corresponds to a center-of mass (CM) polar angular (θ_{CM}) range of about $0-20^\circ$ for a photon energy of 250 GeV. The BCAL was divided into four layers longitudinally, all of which were steel-scintillator sampling calorimetry. Electromagnetic showers were contained mostly in the first layer, with a small spillover into the second layer. The pattern of longitudinal energy deposition allowed an approximate separation of electromagnetic and hadronic contributions. The energy resolutions were about $\frac{45\%}{\sqrt{E}}$ for electromagnetic particles and $\frac{75\%}{\sqrt{E}}$ for hadronic particles.

The high transverse energy (E_t) trigger was formed using information from MCAL. Analog signals from the four layers in a tower were added, then weighted by the sine of the laboratory polar angle to make signals proportional to E_t for each tower. These signals were then used to form various triggers. For this analysis two trigger types were used, the total E_t or “global” trigger, and the “two-high” trigger. The global trigger required the total E_t in the calorimeter to be above a threshold; this trigger reached full efficiency at a total calorimeter E_t of typically 8 GeV. The two-high trigger required the E_t in any two towers anywhere in the calorimeter to be above a threshold which, for full efficiency, was typically 0.75 GeV. A software threshold slightly above the hardware thresholds removed any biases due to the hardware trigger. The trigger requirement resulted in an effective photon spectrum ranging from about 100 GeV to 400 GeV with a mean of 260 GeV.

A total of four million triggers from the hydrogen target were collected. A small amount of data (about 10% of the photon sample) was collected using a pion beam of mean momentum 250 GeV/c. Data were collected from July 1991 to January 1992. The data presented here represent about 30% of the photon sample and all of the pion sample. Cuts were applied to remove spurious muon triggers, which were about 12% of the triggers. All events were required to have a reconstructable photon energy. In this analysis, no information from the wire chambers has been used. Target empty subtractions of about 20% have been applied to all distributions.

A standard jet-finding algorithm [10] was applied to the calorimeter information in the laboratory frame. A cone in pseudorapidity (η) and azimuthal angle (ϕ) was defined by $R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$. The highest p_t tower in an event was used as a seed to define the zero of $\Delta\eta$ and $\Delta\phi$. A cone of radius $R=1$ was used to define a jet centered around this tower. All towers which fell into this cone were defined to be part of the jet and were used to determine a new jet axis by an energy-weighted sum. The new jet axis was used to define a new cone, and the process was iterated until the jet's p_t converged. The procedure was then repeated to search for additional jets, excluding any towers used in the first jet. Results are presented below for events in which the jetfinder located at least two jets, each of p_t greater than 3 GeV/c and with an average p_t of at least 4 GeV/c. A fiducial cut on laboratory polar angle of 2° to 6° has been made to ensure jet containment in the calorimeter. For a photon energy of 250 GeV, these cuts correspond to θ_{CM} of 44° and 101° respectively. In this polar angular region, the calorimeter had full azimuthal acceptance. The jet p_t spectrum above p_t of 3 GeV/c was identical for the two triggers, and no distinction will be made as to the trigger type in the following discussion.

Evidence for jet production can be seen in a number of distributions. Figure 6a shows an E_t flow distribution for γp interactions. In this plot the higher p_t jet defines $\phi = 0^\circ$. Each calorimeter tower is plotted at the appropriate ϕ from this axis, with the entry being weighted by the tower E_t . The "trigger" jet, near $\phi = 0$ and the "away-side" jet, near $\phi = 180^\circ$ are apparent. The opposite-side jet appears to be broader than the higher p_t jet, but in fact this apparent widening is due to the departure of the azimuthal opening angle between the jets ($\Delta\phi_{jj}$) from 180° event by event. A similar effect has been observed in jets produced in pp interactions [11]. Figure 6b shows $\Delta\phi_{jj}$; the coplanar structure of the events is clear evidence for dijet production.

The data are compared to Monte Carlo events generated using TWISTER V1.2, which generates resolved photons and VDM processes, and LUCIFER V2.2, which generates the direct coupling processes [13]. Within the context of these Monte Carlo simulations, the direct, resolved, and VDM processes are considered distinct. For the resolved processes, the photon structure function used is that of

Duke and Owens [12]. A minimum p_t of the hard scatter of 2 GeV/c has been used, and we have checked that, for events which pass the jet p_t cuts, the results are not sensitive to this cutoff. Effects of energy resolution, shower spreading, calorimeter granularity, and energy spillover from MCAL to BCAL have been simulated. Trigger conditions and all experimental cuts have been applied to the Monte Carlo events. Direct coupling, resolved photon, and VDM processes have been generated with the relative cross sections of 33%, 49% and 18% respectively, as obtained by the integrated parton-level cross sections generated by TWISTER and LUCIFER. These relative fractions depend slightly on the parton distributions used. After triggering and jetfinding, the relative contributions were 43%, 53% and 4% for direct, resolved and VDM respectively. The energy spread of the beam has been simulated by generating Monte Carlo events at six different energies, in ratios appropriate to reproduce the observed triggered energy spectrum. We have used the independent fragmentation [14] option in the Monte Carlo calculation; all other parameters have their default values. String fragmentation [15] gives similar results, but we find that independent fragmentation gives a better overall representation of our data. Figure 6 shows the comparison of data and Monte Carlo simulation. We see that agreement between the Monte Carlo simulation and the data is quite reasonable.

In the simple Born-level picture, the direct-coupled photon is completely absorbed in the hard scattering process, producing no spectator jet. However, in either VDM or resolved photon processes, a spectator system from the photon is expected. Therefore, a naive expectation is that direct coupling processes should have little or no energy in the photon direction, while resolved or VDM processes should produce substantial forward energy. It is therefore interesting to look at the forward energy flow into the beam calorimeter. Electromagnetic energy in the BCAL is subject to effects from pileup from nearby RF buckets as well as multiple soft photons accompanying the high energy photon which initiated the interaction. To avoid these problems, we estimate the hadronic energy in the beam calorimeter, based on the pattern of longitudinal energy deposition. We define the beam calorimeter hadronic energy to be the sum of the energies in the back three layers, with a slight correction to layer-two energy for spillover of electromagnetic energy

from layer one. This algorithm underestimates the hadronic energy slightly, but it is insensitive to beam pileup or multiple soft photons. Data and Monte Carlo have been treated identically.

Figure 7 shows the beam calorimeter hadronic energy divided by the incident photon energy for events with two jets with an average p_t of 4 GeV/c or more. The most prominent feature of the data is a sharp peak at small values of forward energy which contains more than half of the events. In addition, there is a tail which extends to 0.3. The Monte Carlo curve reproduces the data reasonably well. Figure 7 also shows the Monte Carlo expectations for the contributions from the three subprocess to the forward energy flow. All three components exhibit the peaking at small forward energy with a tail extending out to higher energy. The distributions for the resolved and direct processes are quite similar in the region below 0.15, which contains most of the data.

The pion data serve as an important comparison to the photon data, since πp interactions have no direct component, except possibly for a small higher twist contribution [16]. Figure 8 compares the BCAL hadronic energy for pion and photon data. In order to match the energy range for the pion data, beam energies from 200–300 GeV have been used in this plot. Also, due to the poorer statistics for the pion data, the p_t cut in this plot is 3.8 GeV/c rather than 4 GeV/c. Neither of these differences has a significant effect on the distributions. The forward energy distributions for the pion and photon data are surprisingly similar; in particular the pion distribution is also dominated by a peak at small BCAL energy. The forward energy decreases with an increasing p_t cut, as expected from energy conservation, but the similarity of the forward energy for γp and πp events is independent of the p_t cut. However, pion and photon data do show substantial differences in many other distributions, such as E_t flow, E_t not associated with either jet, and $\Delta\phi_{jj}$. [17].

We conclude that there is not a clear separation of events into “direct” and “resolved” categories based only on forward energy flow. Contrary to naive expectations, Monte Carlo simulations indicate that direct and resolved processes have similar forward energy distributions. This conclusion is supported by the similarity

of forward energy distributions for jets produced in πp and γp interactions. Within the context of the Monte Carlo simulations, the similarity arises because the resolved photon events, which have a forward-going beam jet, often deposit little or no energy in the forward direction, due to fluctuations in the beam jet fragmentation. And the direct-coupled events occasionally produce significant energy in the forward calorimeter due to fluctuations in the fragmentation of the high p_t partons. We conclude that a clean separation of direct coupling from the other subprocesses will require additional information, such as angular correlations and energy conservation constraints.

In summary, we have observed dijet production in γp interactions. The E_t flow and $\Delta\phi_{jj}$ distributions show clear evidence for jet production, in agreement with expectations from QCD. The data are in good agreement with a QCD Monte Carlo simulation which has contributions from direct coupling, resolved photon, and a small contribution from VDM processes. A somewhat surprising result is that the forward energy flow is very similar for pion-induced and photon-induced dijet events. However, within the context of the Monte Carlo simulation, this similarity is expected, since the forward energy flow is similar in the direct and resolved processes.

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Table 1

Target	Raw Triggers	Dijets, $p_t > 3$
LH2	3.6M	54K
LD2	3.0M	45K
Nuclear	3.5M	45K

FIG. 1

FIG. 2

FIG. 3

+

FIG. 4

FIG. 5. Experimental apparatus. C1, C2, B1 and B2 are beam scintillators, PWC's are proportional wire chambers, DC's are drift chambers.

FIG. 6a. E_t flow per event for events with average jet p_t greater than 4 GeV/c. The higher p_t jet defines $\phi = 0$, and each calorimeter tower is plotted at the appropriate ϕ , weighted by the tower E_t . The solid line is data; the dashed line is Monte Carlo events, as described in the text.

FIG. 6b. $\Delta\phi$ between the jets for events with average p_T greater than 4 GeV/c. The solid line is data; the dashed line is Monte Carlo. The Monte Carlo curve is normalized to the same number of events as the data.

FIG. 7. Hadronic energy in the beam calorimeter divided by the photon energy, for dijet events with average p_t greater than 4 GeV/c. The diamonds are data, the curves are Monte Carlo. The solid histogram is all processes, the dotted histogram is the direct coupling contribution, the dashed is the resolved photon, and the dot-dash line is the VDM contribution. The Monte Carlo is normalized to the same number of events as the data.

FIG. 8. Hadronic energy in the beam calorimeter divided by the beam energy, for dijet events with average p_t greater than 3.8 GeV. The solid diamonds show γ -proton events, and the open squares show π -proton events. The π -p curve is normalized to the photon data.

2 of 2

Work on E-761 Hyperon Radiative Decays

(J. Chilton, T. Dubbs, J. Langland,
(E. McCliment, C. Newsom)

Introduction

Approximately 2 years ago, the last data tape was written for experiment E-761. We are now well into the data analysis phase of the experiment, with many studies having now been completed. Tim Dubbs¹ has obtained his Ph.D. during this period and a new graduate student, J. Langland² has joined in the analysis of the E-761 data, with the goal of obtaining his Ph.D. for this data.

Work Completed and in Progress

There are a very large number of physics topics available for study in the E-761 data set (approximately 1000 tapes). Some of these topics presently under study or completed are given in Table I.

TABLE I

$\Sigma^+ \rightarrow P + \gamma$	high precision branching ratio
$\Sigma^+ \rightarrow P + \gamma$	high precision asymmetry
Σ^+	polarization versus p_t and x_f
Σ^+	high precision magnetic moment
Σ^+	magnetic moment via crystal channeling
anti(Σ^+)	production polarization
$\Xi^- \rightarrow \Sigma^- + \gamma$	branching ratio, asymmetry
Ξ^-	production polarization
Σ^+ and Ξ^-	beam fluxes versus p_t
Σ^-	production polarization

¹ Task A funds were used in part for these studies. The results are presented in that section by his thesis advisor, E. McCliment.

² Advisor, Y. Onel.

Of these topics, the following papers have been published or accepted for publication:

- Measurement of the Asymmetry Parameter in the Hyperon Radiative Decay $\Sigma^+ \rightarrow p\gamma$.³
- First Observation of Magnetic Moment Precession of Channeled Particles in Bent Crystals.⁴
- Polarization of the Σ^+ and Anti(Σ^+) Hyperons Produced by 800 GeV/C Protons.⁵
- Measurements of the Magnetic Moments of the Σ^+ and Anti(Σ^+) Hyperons.⁶

In addition, the following papers have been submitted or are in draft form.

- Measurement of the Branching Ratio for the $\Xi^- \rightarrow \Sigma^- \gamma$ Radiative Decay.⁷
- P_t and X_f Dependence of the Polarization of Ξ^- Hyperons Produced by 800 GeV/c Protons.⁸
- A New Upper Limit on the Branching Ratio of the $\Omega^- \rightarrow \Xi^- \gamma$ Radiative Decay.⁹
- The Branching Ratio of Anti(Σ^+) $\rightarrow \bar{p}\gamma$, A Test of CP in Hyperon Decay.¹⁰
- Measurement of the Magnetic Moments of Short-Lived Particles Using Channeling in Bent Crystals.¹¹
- Measurement of the Branching Ratio and Asymmetry for the $\Sigma^+ \rightarrow p\gamma$ Radiative Decay.¹²

The above drafts are nearing final form and should be submitted in the near future. The beam fluxes and numerous polarization studies remain to be done,

³ M. Foucher et al., *Phys. Rev. Lett.* **68**, 1992.

⁴ D. Chen et al., *Phys. Rev. Lett.* **69**, 1992.

⁵ A. Morelos et al., *Phys. Rev. Lett.* **71**, 1993.

⁶ A. Morelos et al., accepted by *Phys. Rev. Lett.*, October 1993.

⁷ T. Dubbs et al., submitted to *Phys. Rev. Lett.*

⁸ A. Morelos et al., final draft form.

⁹ I. Albuquerque et al., draft.

¹⁰ R. Mahon et al., draft.

¹¹ V. Baublil et al., draft for *Nucl. Instrum. Methods*.

¹² P. Cooper et al., draft for *Phys. Rev.*

and are being worked on by J. Langland¹³ and S. Timm,¹⁴ respectively. The beam fluxes are particularly critical since they are urgently needed by SELEX (E-781) for the beam design studies. They should be completed within the next year, with publications to follow thereafter.

Additional topics such as three body decays with one photon are being studied to determine if sufficient statistics have been written to tape to justify an analysis of these data.

¹³ University of Iowa.

¹⁴ Carnegie Mellon University.

Work on WA89 Charmed Baryon Studies at CERN

(C. Newsom)

Introduction

In 1989, the WA89 group took its first engineering run. Two years later, in 1991, the first set of “real” data was taken, putting approximately 80 million interaction triggers to tape. Finally, in 1993, after significant hardware upgrades (Figs. 1 and 2), an additional 100 million interaction triggers were taken. Analysis of these data, preparation of production analysis software, as well as participation in the data run of 1993 has been the primary goal of one of us (CRN) during his sabbatical and subsequent summer at CERN. After much hard work by everyone in the group, all of these efforts are starting to bear fruit. Altogether five charmed baryon states have been seen, plus two excited states! These results and their significance will be discussed in the following sections.

Analysis of the 1991 Data

The analysis of the WA89 data was important to all of us for several reasons. First, the physics is interesting. Second, to SELEX members, there were two critical aspects of the production mechanisms that needed to be measured and understood. The first aspect was to verify that the use of a Σ^- beam would result in a large leading effect implying the production of large numbers of Λ_c baryons. If this effect is verified, it is then hoped that Ξ_c baryons would also be produced in large quantities. If true, then SELEX would produce more than 100 times the statistics of these particles in this next generation experiment. Both of these effects are now known and will be discussed in the following sections.

D^- and Λ_c^+ Production

The first reaction to be seen in this experiment was the $D^- \rightarrow K^- \pi^+ \pi^-$. This decay is fairly easy to study due to its long lifetime, and the two different particles in the final state, which allow the RICH to be used for good particle identification. The next decay to be studied is the $\Lambda_c^+ \rightarrow p K^- \pi^+$. This decay is also particularly

amenable to particle identification using the RICH detector. The D^- and Λ_c^+ mass plots and x_f distributions are shown in Figs. 3 through 5. If one assumes that the x_f distribution is of the form $(1 - x_f)^n$, then for D^- production one gets $n = 6.3 \pm 1(\text{stat})$. This is consistent with the range of values found for D production found using pion and photon beams. For Λ_c^+ production $n = 3.7 \pm 1.3(\text{stat})$. Clearly the x_f distribution for charm baryon production falls off quite slowly, as compared with charmed meson production from photon or pion beams, implying a significant leading effect. The use of a Σ^- beam thus yields significantly more charmed baryons than would be found with pion or photon beams at large x_f .

Σ_c Production

Once a clear Λ_c^+ signal has been seen, the next logical step is to combine them with pions to look for the Σ_c . The results of this search are shown in Figs. 6 and 7. Clear signals for Σ_c^0 and Σ_c^{++} are seen. Additional analysis is ongoing.

Ξ_c Production

In parallel to the above searches, we were also looking for evidence of Ξ_c decays. These were first seen by combining reconstructed Λ^0 and Ξ^- decays to yield the Ξ_c . It was not at all clear at the beginning of this search that significant numbers of this charmed-strange baryon would be seen. The decay modes that we have examined so far are

- $\Xi_c^+ \rightarrow \Lambda K^- \pi^+ \pi^+$
- $\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$
- $\Xi_c^0 \rightarrow \Lambda K^- \pi^+$
- $\Xi_c^0 \rightarrow \Xi^- \pi^+$.

The results of this search are shown in Fig. 8. These results are particularly exciting when compared with the Λ_c results. One should note that roughly equal numbers of charmed and charmed-strange baryons are seen. This is entirely different from the results of pion and photon beams, where the charmed-strange baryons are much reduced (factors of 100) with respect to the charmed baryons! Clearly, the use of a hyperon beam has great advantages for the production of charmed-strange baryons.

Excited States and Radiative Decays of Charmed Baryons

In addition to the search for charmed and charmed-strange baryons, one can also look for excited states and radiative decays of these same baryons. This has been done by looking at the following spectra:

- $M(\Lambda_c^+ \pi^{+,0}) - M(\Lambda_c^+)$
- $M(\Lambda_c^+ \pi^0) - M(\Lambda_c^+)$
- $M(\Xi_c^+ \gamma) - M(\Xi_c^+)$.

The results of this search are shown in Figs. 9 and 10. Not only do hyperon beams yield large numbers of charmed-strange baryons, but also significant numbers of their excited states.

Hardware Upgrades for 1993

Of the many hardware upgrades made by the group to this experiment, the major contribution of Iowa to WA89 was in two systems. During the 1991 run, extensive analysis indicated that the two major weaknesses lay in the construction of the target and the silicon beam/vertex detector systems. The major problems in the silicon system were caused by several related things. First, much of the silicon was 50 micron pitch. This strongly limited the resolution, which is critical for clean separation of the primary and secondary vertices. Second, all detectors were of low efficiency. Third, the detectors were quite noisy. The inefficiency, when combined with the noise resulted in two primary effects. The first was that track reconstruction was inefficient, and often confused by the noise. Second, if the higher resolution plane (25 micron) was missing due to low efficiency, then the resultant increase in track resolution did not allow one to properly assign it to the correct vertex. This resulted in high combinatorics and a correspondingly large background.

The silicon detector project consisted of building three stars of (*xyuv*) detectors placed just downstream of the charm production target. These detectors were $6.5 \times 6.5 \text{ cm}^2$, with a pitch of 25 microns. They were built by the Max Planck Institute in collaboration with Carnegie Mellon University and the University of Iowa. Their design was based upon the detectors used in the test run of E-781. Three major changes were made to the E-781 design, based upon what was learned during

the E-781 test run. First, each SVX had an individual threshold. Even though each SVX threshold was tested before mounting, they were found to have different values after mounting, thus requiring individual thresholds. This allowed us to significantly reduce the noise. The second change that was made was to move the ADC electronics closer to the SVX, thus further reducing noise. Finally, the massive mounts of the E-781 detectors were abandoned for low mass Alumina printed circuit boards. These better match the thermal characteristics of the silicon of the detector, although they are not the best thermal conductors. Typical efficiencies during the 1993 run were 99%, with negligible noise.

The target that was used in the '91 run consisted of two thick pieces of carbon and copper placed side by side. The majority of charmed baryons decay with small x_f . This implies that the secondary vertex will be close to the primary vertex, and thus inside the target. Since these could not be distinguished from secondary interactions of lower energy pions inside the target, all of these events had to be rejected. Thus, one of use (CRN) proposed to purchase several thin (1 mm) diamond targets and replace the carbon (graphite) target with a segregated target. This was done and the target was successfully used in the 1993 data run. Analysis is in progress.

1993 Data Run and Analysis

In May of 1993, one of us (CRN) traveled to CERN to join the data run, already in progress. The run was just moving into production mode, and each of us was expected to take their fair share of shifts. Another E-781 collaborator, V. J. Smith, of the University of Bristol, who had recently joined WA89 was also participating in the data run. The run went remarkably smoothly with only eight hours of down time due to detector failures.

During the data taking phase of the experiment, off-line software development was in full swing. Iowa (CRN) was asked to write a track matching routine between the silicon detector space tracks and the "matched" tracks in the downstream spectrometer. This involved a close collaboration with many others since the silicon space track finder was being simultaneously written. The presence of

massive Zbook usage made this task particularly difficult. This project was completed successfully just before the departure of CRN to Iowa and Fermilab for the rest of the summer. The software is now being used in the primary data production program.

Figure 1. WA89 experimental set-up in 1991

Figure 2. WA89 experimental set-up in 1993

Figure 3. $pK^-\pi^+$ invariant mass spectrum

Figure 4. x_F distribution for D^- .

Figure 5. The differential distribution for Λ_c produced in the copper target.

Figure 6. Mass difference spectra: $pK^-\pi^+\pi^- - pK^-\pi^+$ with a cut on the Λ_c^+ mass within 10 MeV/c² (solid) and off the Λ_c^+ mass (dashed with arbitrary normalization).

Figure 7. Mass difference spectra: $pK^-\pi^+\pi^+ - pK^-\pi^+$ with a cut on the Λ_c^+ mass within 10 MeV/c² (solid) and off the Λ_c^+ mass (dashed with arbitrary normalization).

Figure 8. Invariant mass spectra for $\Lambda K^- \pi^+ \pi^+$ and $\Xi^- \pi^+ \pi^+$ depicting a signal for the Ξ_c^+ and $\Lambda K^- \pi^+$ and $\Xi^- \pi^+$ depicting a signal for the Ξ_c^0 . Note the similar visible yield for both charge states.

Figure 9. Mass difference spectra: left: $pK^-\pi^+(\pi^-\text{ or } \pi^0 \text{ or } \pi^+)-pK^-\pi^+$ with hard cuts for the identification of Λ_c^+ ; right: $pK^-\pi^+\pi^0-pK^-\pi^+$.

Figure 10. Mass difference $\Xi_c^+\gamma - \Xi_c^+$ for two decay modes of the Ξ_c^+ . The shaded area corresponds to the background outside of the Ξ_c^+ peaks.

Work on E-781 Charmed Baryon Studies at Fermilab

(N. Akchurin, J. Chilton, J. Langland, E. McCliment,¹⁵
C. Newsom, Y. Onel)

Introduction

The University of Iowa is contributing significantly to the hardware of E-781. Specifically, two silicon detector systems, drift chambers and MWPCs will be contributed. Detailed summaries of each of these systems are found in the following sections.

Silicon Detector Status

(N. Akchurin, J. Chilton, C. Newsom, Y. Onel)

The University of Iowa is involved in the construction of two silicon detector systems. The first system is a beam detector (BSSD) and consists of two stations of XYU planes with a third XY station sandwiched between. These $2 \times 2 \text{ cm}^2$ detectors each have 20 micron pitch and are read out by SVX-H electronics coupled with specially designed fastbus modules being designed and built at the St. Petersburg Nuclear Physics Institute.

The second system (TSSD) is a mosaic of two layers of four planes placed about one third of the way into the first analyzing magnet. These $6.5 \times 6.5 \text{ cm}^2$ detectors each have a pitch of 25 microns, with every other strip being read out by SVX-H electronics. The primary purpose of this detector is to allow the software trigger to quickly determine if a stiff track of the required sign (+) is present. If not, the event is rejected. A secondary purpose is to allow a rough sign and momentum to be assigned to tracks before significant bending can occur. This vastly simplifies the track matching downstream of the magnet, since both bend-plane and non-bend-plane information can be used and the area of search is reduced to a small window.

¹⁵ Work by E. McCliment was performed with Task A funding and is reported in that section.

Aluminum Nitride thick film printed circuit boards are being constructed for these detectors to minimize mass and maximize heat transfer. This is needed due to the large amount of heat generated by the SVX-H and the associated individual regulators. In addition they are well matched in their thermal expansion properties. The design of the boards are complete for the $2 \times 2 \text{ cm}^2$ detectors and prototypes will be ordered soon. Design of the boards for the mosaic detector will expand upon the design of the smaller detector as soon as the prototype boards are tested and found to be error free. The design of the stands of both detector systems is complete, and a prototype of the $2 \times 2 \text{ cm}^2$ stand has been built. Construction for the smaller boards will begin soon. All silicon wafers have been ordered and received. Construction and assembly is expected to proceed carefully during the next 12 months, with installation planned for late 1994. This is compatible with the present Fermilab schedule of beam in late 1995.

Status of Drift and Multiwire Proportional Chambers

(N. Akchurin, J. Langland, E. McCliment,¹⁶ Y. Onel)

In the past, in collaboration with University of Trieste/INFN-Trieste, our group operated and maintained several multiwire proportional chambers (MWPC) for E-704 at FNAL. They are mostly 2 mm wire pitch and equipped with RMH(CERN) readout standard. Typical gas mixture is *magic gas* with relatively high gain. Dimensions are given below. The items 5–6 were originally used by MPI-Munich at E-665 at FNAL.

<u>Module</u>	<u>Dimensions</u>	<u>Planes</u>	<u>Spacing</u>	<u>Wires/plane</u>
1	$0.5 \times 0.5 \text{ m}^2$	<i>xyuv</i>	2 mm	256
2	$0.5 \times 0.5 \text{ m}^2$	<i>xy</i>	2 mm	256
3	$0.65 \times 0.65 \text{ m}^2$	<i>xyuv</i>	2 mm	320
4	$0.65 \times 0.65 \text{ m}^2$	<i>xy</i>	2 mm	320
5	$0.75 \times 1.40 \text{ m}^2$	<i>xyu</i>	2 mm	approx. 500
6	$0.75 \times 1.40 \text{ m}^2$	<i>xyu</i>	2 mm	approx. 500

¹⁶ Work was performed with Task A funding and is reported in that section.

Our group has built six planes of large drift chambers (five planes of conventional drift chambers and one plane of delay line chamber) for E-683 at FNAL. These chambers are in working order and can be implemented for use in E-781. There are two planes per gas tight box. We operated the chambers with 50% argon + 50% ethane bubbling through 0.1 degree isopropanol with over 96% efficiency during data taking. The planes noted as x' are half cell staggered to remove the left-right track ambiguity. Typical parameters are given below.

<u>Module</u>	<u>Dimensions</u>	<u>Planes</u>	<u>Cell Size</u>	<u>No Wires</u>
1.1	$1.50 \times 2.50 \text{ m}^2$	x	2.4-2.8-3.2 cm	84
1.2	$1.50 \times 2.50 \text{ m}^2$	x'		85
2.1	$1.50 \times 2.50 \text{ m}^2$	x'		85
2.2	$1.50 \times 2.50 \text{ m}^2$	x		84
3.1	$1.50 \times 2.50 \text{ m}^2$	x		85
3.2	$1.50 \times 2.50 \text{ m}^2$	Delay line		84 (top) 84 (bot)

These detectors will be installed in PC4 as soon as the major mechanical and electrical construction work in that area is complete.

Summary and Conclusions

We will be continuing with our data analysis on E-683 (photoproduction of high transverse momentum jets using photon beam) to extract the cross sections of the QCD subprocesses, i.e., QCD computer effect and quark-gluon fusion. We also hope to finalize E-704 (spin physics with incident protons and anti-protons) data analysis on the Λ production.

Our ongoing involvement in the analysis of Fermilab experiment E-761 is now slowing as that experiment nears completion. Analysis of this data will continue for about one year, with the concentration on analysis and publication of the negative beam data sample.

During the summer of 1994, we will be participating in the final run of the WA89 hyperon experiment at CERN. No conflicts are foreseen with the installation of detectors for SELEX.

The largest effort by Iowa in the installation of E-781 will occur in late 1994. The installation of the upgraded Iowa silicon beam and trigger detector systems will occur, as well as the associated Faraday cage/climate control system. We will also provide and install the Iowa drift chambers in the E-781 area (6 planes) and 5 MWPC (15 planes). In parallel with the installation of the silicon, hardware and software test systems will be designed and tested on the silicon, and integrated with the full data-acquisition system. E-781 is presently scheduled to run in late 1995 and should run for roughly one year.

TASK C

GEM and SSC Related R&D

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GEM and SSC Related R&D

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Looking to the future, we believe that the University of Iowa High Energy Physics Group should be involved in SSC detector development, so that when it comes on-line the group will be in a position to participate in experiments there. We are a member of the GEM (Gammas, Electrons, Muons) collaboration which has showed interest in constructing a major SSC detector. The members of this collaboration from the University of Iowa are Yasar Onel, Ed McCliment, and C. Newsom (Experimental HEP faculty), Yannick Meurice, M. Halsie Reno, and V. Rodgers (Phenomenology/Theory HEP faculty), N. Akchurin (Experimental HEP Research investigator), S. Bravar, and J. Langland (graduate research assistants). We are part of the calorimetry group of the GEM collaboration. We are also involved in the two related R&D projects on scintillating calorimetry for the SSC detectors. These are: (a) R&D on the scintillating fiber calorimetry for the SSC detectors (SSCintCAL or Spaghetti Calorimetry). We recently have been funded jointly by the Office of Superconducting Super Collider division of DOE, the HEP division of DOE, and TNRLC for this project. This project now has a new name Scintillating Barrel Calorimetry (SBC). (b) Ultrafast readout of scintillating fibers using upgraded position sensitive photomultipliers. This project has been approved at CERN by LHC (Large Hadron Collider) Detector R&D committee and independently by SSCLab Generic R&D committee and it is called RD17.

GEM

A new international collaboration (GEM) has been formed to propose the design and construction of a large detector for the SSC [1]. Building on the previous work of the L* and EMPACT/TEXAS collaborations, we were able to form a strong core for the new collaboration, which intends to propose a major detector combining precision measurements of leptons and photons, and robust muon detection for the SSC. This collaboration includes almost the entire set of U.S. groups from both the L* and EMPACT/TEXAS Letters of Intent as well as several important new groups who have not been previously involved in SSC proposals. This represents a strong core around which to build the plans for this detector.

The physics goals of a large high p_T detector for the SSC are centered on the topics that form the main justification for the construction of the SSC—namely the elucidation of the physics behind the electroweak symmetry breaking that is expected to explain the mass spectrum of the physically observed gauge bosons and fermions. This implies the search for the Higgs boson, technicolor, supersymmetry, as well as the search for new quarks, leptons, Z s and W s. In addition to these topics, one has always to prepare for the unpredicted or unknown new phenomena that nature might have in store for us. These considerations, as well as the realization that some of these searches might necessitate the highest luminosities attainable at the SSC, lead to the desirability of two large high p_T 4π detectors with complementary capabilities.

Progress on Generic SSC Related R&D

Ultrafast Readout of Scintillating Fibers Using Upgraded Position-Sensitive Photomultipliers

This R&D collaboration (FAROS) consists of CERN, U. of Iowa, LAPP, Annecy, INFN (Messina, Trieste), IHEP, Serpukhov, Kyoto, and Osaka.

We propose to improve the performance of position-sensitive photomultipliers and with it to realize an ultrafast-readout device of scintillating fibers. This should play a unique role in the complex of a future vertex detector, owing to its inherent subnanosecond-resolving time as well as its capability of an extremely high counting rate.

Our proposal is first aimed at upgrading the position-sensitive photomultiplier, in particular, its space and time resolutions. Full advantage of the new phototube will be demonstrated in its immediate application to a generic prototype of a scintillating-fiber detector. Our program also includes intensive R&D on a real-time digitization of the multihit topology, which should provide an essential back-up to the vertex tracking at extremely high rates, one of the most difficult problems relevant to the expected high performance of the SSC/LHC Colliders.

The FAROS [2] proposal has been approved at CERN by the LHC detector R&D committee as a Generic detector project. We also have funding for this project

from SSCLab. CERN has already agreed to equip and operate the T7 beam line and to provide floor space and the usual infrastructure for the counting room.

Proposed R&D by the University of Iowa Group

- Design of Trigger Logic for test
- R&D on Front-end electronics real-time digitizer (RTD) design, improvement, and construction
- Monte Carlo simulations on topological trigger device (TTD)
- Running the tests in T7, PS, CERN
- Data analysis.

Introduction

With the development of high quality small diameter scintillating fibers (SciFi) and of fast multichannel position-sensitive photomultipliers (PSPM) [3], the *scintillation counter* technique is continuing to find large applications in nuclear and particle physics [4]. In addition to its traditionally inherent merits like fast response, high gain, low noise, and simple and reliable operation, this development has led to the achievement of high spatial resolution.

As an additional bonus, the upgraded dynode structures (mesh or fine grid) developed in view of obtaining localization properties in the PSPM provide an increased immunity to magnetic fields. Studies of the magnetic properties of these PSPMs are underway and will be the subject of a future publication.

We report on recent progress in the construction and operating experience of optimized prototypes of hodoscopes based on SciFi arrays coupled to a PSPM in order to measure with high accuracy the spatial position of charged particle trajectories, with fast timing properties that make such detectors particularly suited to applications in the high luminosity environment of future high energy colliders.

These studies are the natural continuation of an earlier study using coarser prototypes with 1 mm diameter fibers.

Description of the Prototypes

Mechanical structure

We have constructed a small hodoscope with 0.5 mm diameter scintillating fibers. As illustrated in Fig. 1, the SciFi hodoscope, 28 mm wide, consists of 5 single layers of fibers assembled by staggering each layer by 0.25 mm (Fig. 1). On the readout edge, the SciFi array is split into 4 segments of 7 mm each. Each segment is stretched over 35 mm on the photocathode (Fig. 1) so as to provide a magnification factor $\alpha = 5$, and a space resolution of $\sigma = 200\mu\text{m}$.

A commercially available 3 inch diameter PSPM (R2486) manufactured by Hamamatsu Photonics was used in the present study. The electron shower as amplified by the 12 dynodes is read with 16x and 16y crossed wire anodes.

Readout electronics

The electronics are shown schematically in Fig. 2. Each anode (of each x and y array) is connected to a common delay line with identical delays. One can thus measure the relative time difference between the PMT anode pulses emerging from the two ends of the delay line. The anode pulses are then amplified*, discriminated (constant fraction or leading edge) and then fed into a TDC, a monitoring circuit (not shown), and a Real Time Digitizer (RTD). Using the timing information from the x delay line, one can determine the segment which was hit. Similarly, from the y delay line, one gets the position within the segment.

Experimental Results

We have installed the apparatus in a test beam (5-10 GeV/c pions and protons) of the CERN Proton Synchrotron (Fig. 3). It consists of 2 beam defining counters S1 and S2, two narrow finger counters S3 and S4 (0.5 mm wide across the beam) and three SciFi-PSPM hodoscopes. HA1 and HA2 are of identical construction, while HB is made of two parallel SciFi arrays movable with respect to each

* A 100x amplification is presently needed because the gain of the PSPM is $10^5 - 10^6$.

other, in order to simulate two track events. With this versatile setup we studied the space and time resolution of our hodoscopes, as well as the imaging and multi-track properties.

Space resolution

The space resolution of the hodoscopes was first studied using a self calibrating method by selecting track definition fibers of the SciFi array at a given interval and extending them to a second small PMT. Figure 4 shows the results obtained with 7 GeV/c positive beam particles. After unfolding the effect of the width of the definition fibers (0.5 mm diameter) the resolution is estimated to be $\approx 200 \mu\text{m}$, which is fairly close to the expected value based on the properties of the presently available PSPMs.

Similar results were obtained by using two 0.5 mm wide definition counters placed up and down stream of the hodoscope.

Linearity of the reconstructed position

The linearity of the reconstructed position was measured by scanning the full width of the SciFi array with a finger counter, 0.5 mm wide, by steps of 0.5 mm. The results are seen in Fig. 5.

The linearity within each of the 4 segments is quite good. Small non-linearities are seen near the boundaries. This effect is most likely due to the edge of a segment being near the edge of the PSPMs active area. Note that the width of the segments (35 mm), is seen by 12 anodes each separated by 3.75 mm. This configuration provides only one *guard* anode beyond the SciFi array extremities.

SciFi/PSPM detection efficiency

The spatial detection efficiency has been studied by normalizing the number of events detected by the last dynode of the PSPM with respect to the incident flux as defined by the finger counter. This *raw* efficiency, not including any losses by the RTD, is plotted in Fig. 6 over the full width of the SciFi array. It is greater than 90% almost everywhere, except at the boundaries of the SciFi segments. This

average efficiency is due mostly to the amount of light produced in the fibers, and the attenuation length within the fiber.

Note that the areas of lower efficiencies correspond to a periphery of $d \approx 5.0$ cm on the photocathode of ≈ 6 cm in the nominal diameter. Another local effect that was previously observed at each break between adjacent segments of the fiber array on the photocathode has been improved by arranging the segments on the photocathode in alternate directions. This guarantees that the fibers that are adjacent in the detector remain adjacent on the PMT face, even though they fall in different segments.

In order to maximize the efficiency, it proved useful to place a reflector on the opposite end of the fibers. Optical contact between SciFi and the photocathode was made with silicon grease. In this connection it is important to understand that the quality of the scintillating fiber as well as the geometry of the array structure affect the efficiency. For example, the stacking of 5 single layers locally provides only 2 fibers traversed by incident particles. Assuming the thickness of the cladding is $\approx 3\%$ of the fiber diameter ($\approx 15 \mu\text{m}$ for 0.5 mm fibers) the portion of such a *weak* region presents $\approx 6\%$ of the array surface. A fine structure often seen in the local efficiency can be explained by this effect.

Time characteristics

Another important issue concerns the time characteristics of the readout system based on the delay-line method. The time characteristics were studied by computing the mean time, $t_L + t_R$, with respect to a reference time t_0 , where t_L and t_R are the TDC contents corresponding to the arrival times of the left and right propagating signals coming out of the delay line, and t_0 is generated by either the last dynode of the PSPM, or an external counter. Figure 7 shows the $(t_L + t_R)$ distribution with respect to t_0 as defined by the last dynode signal of the PSPM. The two peaks were obtained by adding a delay of 10 ns to t_0 in order to provide a calibration of the time scale.

The resolving time of $\sigma \approx 0.7$ ns can be interpreted mainly as an *internal* time spread of the last dynode signals with respect to the corresponding anode signals.

Such a good time resolution will allow a fast strobe coincidence at the level of the RTD, as is required for two hit discrimination.

Figure 8 presents a similar result obtained with t_0 defined by an external counter. Assuming that the time resolution of the external counter is comparable with that of the PSPM the total resolving time of the hodoscope is estimated to be $\sigma \approx 1.5$ ns.

Two-dimensional imaging

The spatial resolution as achieved with this prototype allows us to obtain two dimensional images; as an example, in Fig. 9, is shown the profile of a scintillator shaped as the letters "HC," placed in the beam just downstream the hodoscopes. This profile is obtained in real time from 2 planes of SciFi hodoscopes gated by the shaped scintillator.

Two-Hit Resolution

The second hodoscope prototype (referred to as type B), shown in Fig. 10, is dedicated to the study of the two track spatial resolution. Two track events can be simulated by a double array structure providing one of the array movable with respect to the other. Both arrays are seen by the same rows of pad anodes of a R3941-Mod. PSPM, custom manufactured by Hamamatsu.

As shown in Fig. 11, the anode signals from the delay line of the hodoscope are connected to the CFD discriminators. The pictures in Fig. 12 show typical examples of "simulated" two track events produced by 10 GeV/c beam particles passing through the hodoscope, as a function of the relative displacement of the two fiber arrays. Changing the separation (d) between the two hits from 0 to 5 mm, the discriminator correctly triggers down to 3 mm.

General Discussion

Improving commercially available PSPMs, such as the R3941 produced by Hamamatsu Photonics, and creating new PSPMs by using finer grid dynodes is planned. The space resolution under an axial magnetic field of ≈ 500 G should

provide an intrinsic resolution of ≈ 2 mm in FWHM against the present 8 mm resolution.

A PMT readout system based on a delay line has not been used for the real-time digitization until now. A delay line less than 50 ns long is well suited to the moderate intrinsic spatial resolution of the PSPM and the use of this purely passive element makes its readout simple, inexpensive, very fast and reliable. In the near future the FAROS group will concentrate on the improvements of the time characteristics of whole the readout system. This is necessary not only for high rate performance but also for good reconstruction of multi-hit events in real time.

The number of photoelectrons emitted from the photocathode of the PSPM is inferred to be about 4 photoelectrons from the measurement of the spacial resolution. Some new SciFi ribbons developed by the Nagoya University yielded 10 photoelectrons for 4 layers of 0.5 mm fibers (SCSF38-KURARAY), yielding a clean pulse height spectrum, well separated from the background noise (Fig. 13).

Conclusion

It is clear from the present studies that the commercially available PSPM constitutes a promising step toward a novel *high space and time resolution* detector.

With a spatial accuracy better than 200 μm , a time resolution of 1.5 ns, a two-hit separation of 3 mm, good linearity and an efficiency better than 90%, this type of detector is already an attractive candidate for high rate topological triggering and tracking applications in particle physics and accurate real time imaging. Relatively simple construction techniques and moderate cost per anode channel, due to the delay-line readout system, are quite encouraging in view of the needs of future large scale systems.

In addition, there is ample room for improvements based on the present results and in view of forthcoming developments in the field of upgraded PSPMs. Future efforts will also be dedicated to improving the quality of the SciFi arrays as well as the time characteristics of the front-end electronics.

Generation of events using ISAJET, minimum bias, Higgs $\rightarrow$ 4 Leptons ($M_H = 800$ GeV), follow-up of tracks (including second vertices, multiple scattering, etc.), trigger algorithms (isolated high $p_\perp$, tagging jets, etc.).

In the following, we describe our progress during FY 1993.

Progress on GEM/SSC Related R&D

In the past few years, SSCintCAL Collaboration [5] constructed a number of prototypes of depth-segmented fiber calorimeters and for the most part tested their performance in a test beam environment. We have played a major role in this effort, especially at the Fermilab and BNL test-beam work. Two of our graduate students have obtained their M.S. degree theses (Dan Kadrmas, Jerry Langland).

1. Test of the existing prototypes

Testing of the existing prototypes was our highest priority for this R&D effort. We used the MP9 beam line during the second part of the fixed-target run at Fermilab (T-840) [5]. We have had experience with the MP9 beam before and therefore assumed responsibility for this part of the activity. Our responsibilities were the following:

- Organization and the control of the beam line and beam diagnostic equipment
- Design and organization of the DAQ and read-out systems in this area; including the operation of a new on-line computer, writing new data acquisition and monitoring programs
- Operation of the gas system for the Iowa-Trieste (E-704) Multi-Wire Proportional Chambers (MWPC)
- Beam chambers (MWPC)
- Writing of tracker-construction software
- Interfacing of new equipment with existing equipment in this area.

2. Data Analysis of T-840 test beam run at Fermilab

- Preparation of the computer programs to read the data tapes and organization of the off-line analysis
- Organization of the off-line data analysis (first pass)
- Preparation of data summary tapes (DST)
- Preparation of technical documents on the off-line data analysis.

3. Cosmic-Ray Test of the modules

- Design and construction of a cosmic ray stand (in collaboration with Fermilab): Due to the space problem at Lab 6, Fermilab we have recently moved the Cosmic-Ray setup to the University of Iowa.

4. Contribution to the construction of two-depth segmented module

5. New Hadronic Calorimeter Prototype construction and BNL Test Beam with the “New Hadronic Prototypes.” We have taken major responsibility for these activities and we have delivered successfully all the items listed below.

- New Hadronic Calorimeter prototypes.
 - Contribution to the construction of the new calorimeter modules
 - Photomultiplier tubes selection
 - Photomultiplier tubes test (source)
 - Photomultiplier tubes bore assembly design and construction
- BNL Test Beam with “New Prototypes”
 - Data-acquisition system setup
 - Design and organization of the DAQ and readout systems; including the operation of new on-line computer, writing data acquisition and monitoring programs
 - Setup of test-beam equipment and operation
 - Contribution to setup of test-beam electronics
 - Contribution to data analysis
 - Contribution to Monte Carlo simulations.

We have fulfilled all of our responsibilities as indicated above for items 1–5.

6. GEM External Calorimeter consists of three major parts:

- Barrel Scintillating Calorimeter with support structure
- End cap passive absorber
- Forward Hadron Calorimeter

We have the following major responsibilities

- Photomultiplier tubes (PMT) development, selection, tests (source, cosmics)
- PMT base assembly development, design, construction and quality control
- R&D on light detectors for calorimeter readout
 - high magnetic environments PMT for test of magnetic field effects
 - study of properties of green-extended PMT (nonmagnetic)
 - design and development work on green-extended photomultipliers (magnetic)
- The stability, monitoring and calibration of a PMT based calorimeter, PMT readout system and calibration assembly, operation, maintenance and quality control.

FNAL T-840 Lead/SciFi Calorimeter

The prototype detector was designed and built by T-840 (FNAL, IOWA, MSU) in the FNAL Lab 6 area. The prototype consists of 30 principal towers arranged in a 5×6 array. Each principal tower consists of a center and side pair of subtowers, the center subtower of each pair is 6 cm square and runs the entire length of the calorimeter, approximately 200 cm. Each side subtower encloses a central subtower and starts approximately 30 cm back from the front of the central subtower with a thickness of about 0.46 cm near the front and 3 cm at the rear. Thus the front of each principal tower is 6 cm on a side, and the rear of the tower is 12 cm on a side.

The towers are constructed of alternating vertical lead and steel plates, with a 2.5 mm and 2.0 mm thickness, respectively. The central subtowers contain 12 lead and 13 steel plates and on each side are seven lead and seven steel plates to complete the side towers (Fig. 14). Each lead plate is cut in a pyramidal form to create the

scaling size of the side subtower, as are some of the steel sheets; however, for structural integrity, some of the steel sheets are cut in larger sections, and span principal towers so that there are groups of six principal towers stacked vertically. Each vertical stack of six principal towers are referred to as a single module. One principle advantage of this, in addition to structural integrity, is that it allows for the study of two different types of tower segmentation, true, physical separations in the horizontal direction, and a somewhat virtual separation vertically.

The photomultiplier tubes used were type EMI 9839b bi-alkali phototubes, 51 mm in diameter, and powered by a LeCroy 1440 HV system. For a large number of runs, Kodak Y7 gilatin filters were inserted between the light guides and the phototubes to improve specific light frequency response. Each PMT could be alternately hooked via 50 Ω cables to a DSP Digital voltmeter, which could in turn be used to calculate currents for source calibration, or to LeCroy 2249 ADC for actual signal response measurements in the traditional manner. ADC readout, for the prototype in the test beam area, along with all other relevant information, such as tracking, tagging, and trigger id, was accomplished via a PDP-11 using a Jorway 411 Interface linked to a Bison Interrupt Module. The PDP subsequently wrote data to a 9 track tape unit and transmitted data over a hardwired link to a VAX 3200 for on-line monitoring and analysis. The VAX 3200 on-line monitoring was done using Fortran-based programs utilizing VAXONLINE Consumer based libraries, and CERN HBook and related routines.

In the MP-9 test beam area the prototype was mounted on a remotely controlled movable table. This table was designed and built by FNAL engineers and technicians to our groups' specifications. The movable table is capable of supporting up to 10 tons of weight and providing both horizontal and vertical translational motion relative to the beam, with both vertical and horizontal rotational motion. The table was controlled remotely by computer operation, and feedback was established by both digital potentiometer readings and visual confirmation, through multiple video cameras in the beam line, with analog instruments attached to the table.

Calibration

A principle concern with projective geometry detectors is calibration [6]. The relative calibration between central subtowers is fairly straightforward since all central subtowers have the same size and are of simple geometric shape. The side towers, however, while all the same size are of nontrivial geometrical shape and are much more difficult to actually calibrate. The hollow and triangular shape of the side subtowers makes source calibration difficult. Further, the fact that in electron showers the majority of energy is deposited solely in the central subtowers, and that in pion showers the energy is spread out through many side and center subtowers, makes relative beam calibration of the side towers difficult. Several techniques were used to calibrate the towers. Two principal methods utilize matrix techniques. The signal in each tower is proportional to the energy deposited in that tower,

$$E_{ij} = \alpha_j A_{ij} ,$$

where E_{ij} is the energy deposited in the j^{th} tower for the i^{th} event, α_j is the calibration constant for the j^{th} tower and A_{ij} is the signal for that tower and event. The central subtower calibration coefficients are:

$$\alpha_l = \sum_k \left(\sum_i E_i A_{ik} \right) (X_{kl}^{-1})$$

with

$$\sum_k X_{jk} X_{kl} = \delta_{jl} .$$

This solution is equivalent to minimizing the energy resolution subject to the constraint that the total energy deposited in the detector is equal to the incident particle energy.

Source Calibration

The Cs 137 source was used to perform localized calibration studies of the detector both during the test beam period as well as before and after the test beam. Initial PMT voltage calibration was done during the test beam period (with no

beam present). The source was guided down the 1.8 mm tubes and PMT voltages were adjusted so that each tower's response was the same. After securing the correct voltages, current values were again read as the source was run through each module. Using this data, relative calibration constants for each tower were determined. For this calculation, and all subsequent calibrations, the overall normalization was set such that central subtower C3C has a calibration constant of 1. An overall normalization to units of GeV was later produced from the electron data (Fig. 15).

Electromagnetic Response Calibration

The above calibration was verified with measurements of the calorimeter's response to electrons. Runs were taken at 50 GeV/c momentum and electron selected beam events were directed down the center of each tower. The resultant calibration agrees to a reasonable extent with the source calibration factors. No systematic trends in any discrepancies between calibrations are noted. The source calibrations, however, are deemed the more reliable. The reason for this is that the electromagnetic shower calibration method is very sensitive to small fluctuations in the side tower energy deposits.

Particle Identification

Ideally a good multi-element calorimeter should be able to distinguish clearly between electromagnetic and hadronic particle types [6]. If so, then this calorimeter could be used as an early level in a triggering scheme. By summing the square of the energy deposited in each tower and dividing by the square of the sum of the energies, one calculates a containment parameter ξ . Better confinement of the particle, implies a larger value of ξ . For a mixed 50 GeV/c beam, (Figs. 16-17) there exists an electron peak near $\xi = 850$, and the larger, broader peak at lower ξ is a pion peak. After adjusting for Cerenkov inefficiency it is found that roughly 90% of electron events have a containment parameter larger than 800 and 98% of hadrons have values lower than 800. This value is the hadron rejection efficiency.

A second method of identification uses a covariance matrix that describes energy deposits and correlations for electron showers in the detector array. This

method involves the construction of a matrix H , which defines the containment parameter ζ for each event.

$$H = M^{-1} .$$

$$M_{ij} = \frac{1}{N} \sum_{n=1}^N (E_i^{(n)} - \bar{E}_i)(E_j^{(n)} - \bar{E}_j) .$$

$$\zeta_m = \sum_{i,j=1}^{18} (E_i^{(n)} - \bar{E}_i) H_{ij} (E_j^{(n)} - \bar{E}_j) .$$

The containment parameter is minimized for of the same type as used to create the H matrix (electrons for example). Therefore, in this case, the smaller value of ζ represents a more electron-like behavior. For a typical mixed 50 GeV/c run (Fig. 18) 90% of the electrons are found to have $\zeta = 26$ or less. Hadrons have containment parameters ranging from the hundreds to the thousands for a typical run at this energy. After correcting for Cerenkov inefficiencies, the hadron rejection efficiency for this method is 99%, with this data set at a 90% electron acceptance.

This particular method manages to achieve a very good electron identification; however, its applicability is somewhat limited. As the angle and point of incidence vary from the position used to calculate the H matrix, the distribution for electrons begins to broaden towards higher ζ . For incident angles greater than 5° virtually no events, electron or otherwise, pass the acceptance cut.

Electromagnetic and Hadronic Resolution

Both the electromagnetic and hadronic resolutions have been studied. At this time preliminary results are only available for early calibrations. Calculations using the most recent calibrations are being done now. Calculations with no momentum cuts yield values on the order of $30\%/\sqrt{E}$ for electromagnetic resolutions with a constant term on the order of 5%. Hadronic calculations yield values on the order of $70\%/\sqrt{E}$ and a constant term of 10%.

Uniformity

Studies of spatial uniformity of the calorimeter towers has also been done. Multiple runs, at various angles, positions, energies, and beam widths have been studied; furthermore, source study correlations have been examined. Tracking accuracy, while somewhat limited, is sufficient to reveal differences in electromagnetic response on the order of a few percent. This nonuniformity appears to also be visible in source calibration studies. Figure 19 shows energy response as a function of position for 50 GeV/c electrons, centered on tower C3.

Energy Loss at Tower Boundaries

As mentioned earlier, for electron showers directed at tower centers, approximately 90% of the electron energy is contained within a single tower (Fig. 20). In the case of pions, better than 90% of the pion energy is contained within the center beam tower and a surrounding block of eight additional towers. More in depth studies, for beam particles not focused on tower centers have also been done. As expected the energy loss at tower boundaries appears to be greater for the horizontal direction (e.g., module B to module C) than the vertical direction (e.g., tower C2 to tower C3). Thus a greater energy loss occurs between the physical module separation than between intra-module interfaces.

GEM Cu/Scintillating Fiber Hadronic Calorimeter Prototype and BNL Tests

Seven projective modules were constructed with laminated copper plates (7.765 mm thick and U-shaped grooves of 3.175 mm deep), copper tubes (1.5 mm ID and 3.175 mm OD) and 1.35 mm diameter 3HF fibers from Bicon. The modules were $15 \times 15 \text{ cm}^2$ in the front and $31 \times 31 \text{ cm}^2$ in the back and the length of the modules was 160 cm. Each module weighed 770 kg. The center-to-center fiber spacing was 8.0 mm in a square lattice configuration. The fiber cladding was $50 \mu\text{m}$ thick. All the fibers ran parallel to the symmetry axis of the modules. The central core of the modules contained ~ 462 fibers that ran the entire length of the module. The rest of the fibers (~ 600), which were in the projective section of the modules

were naturally shorter as required by the geometry. The fiber packing fraction of 2.25% was dictated by the availability of standard copper sheets and tubes. The nuclear interaction length of the modules was $\lambda_I = 15.1$ cm and the radiation length was $\chi_0 = 1.46$ cm. The Molière radius was $\rho_M = 11.6$ mm.

The fibers were bundled together and coupled to a PMT via a hexagonal light guide. We used a 3" green-extended Philips PMT (XP3461B) for these tests because it efficiently matched the emission spectrum of 3HF fibers. The fibers were not screened in any way for light yield, attenuation length or dimensions; they were used as they were delivered by the manufacturer. The front ends of the fibers were not polished nor mirrored due to time constraints. There was no filter in the optical readout chain due to what later turned out to be unfounded concerns about the total light yield.

The modules were stacked such that the central module was surrounded symmetrically by six other modules and the entire stack was placed on a remotely controlled transporter. The transporter was capable of supporting 10 tons and was designed to rotate in both the horizontal and vertical planes. It could also translate the stack of prototypes both horizontally and vertically.

Test Results

The BNL A3 test beam provided electrons, negatively charged pions and muons in the energy range of 1 to 20 GeV. The momentum spread, $\delta p/p$, was $\approx 1.5\%$ for the beamline. The trigger was formed by using appropriate combinations of the signals from two Cerenkov counters, various beam and veto counters, etc. We used 11-bit LeCroy ADCs (Model 2249W) with a 100 ns gate width.

The modules were calibrated with 10 and 15 GeV/c electrons at large incident angles and these calibrations agreed within 2% over a week of running. Light yield studies performed using both LEDs and electron beam gave ~ 60 pe/GeV. The calorimeter response as a function of angle of incidence to electrons qualitatively agrees with SPACAL results, i.e., energy resolution improves with increasing angle of incidence. As expected, there was no appreciable incident angle dependence in response of the calorimeter for pions in the range of $0.5^\circ \leq \theta_V \leq 3.5^\circ$. We also

observed clear separation of the muon signal from the pedestal even at small angles like $\theta_V = 1.5^\circ$ and $\theta_H = 0^\circ$.

Figure 21 illustrates the measured response to 5 to 20 GeV/c single pions. At each energy the response is non-gaussian with some asymmetry and high-energy tail. These effects are mainly due to light attenuation effects in the scintillating fibers and to lateral shower leakage.

The longitudinal shower fluctuations result in a high-energy tail because the light attenuation in the fibers is a function of longitudinal position. Since they are less attenuated, the late developing showers give enhanced light output compared to the early developing showers. As it is shown by SPACAL and others, the use of filters and Al-mirrored ends of fibers give a gaussian response to single pions. The use of a filter eliminates the short wavelength light which in general has shorter attenuation length and large self-absorption.

By suppressing the average response to hadronic activity, the lateral neutron leakage from the stack of modules results in an artificially high e/π ratio. Hadronic showers with a large electromagnetic component are more contained and not suppressed; this combination of mean suppression and stochastic fluctuations for a fraction of unsuppressed showers gives an asymmetric response function.

We also tested a lead/quartz (12 cm $\times$ 12 cm $\times$ 21 cm) calorimeter prototype with 10 GeV electrons. The quartz fiber packing fraction was $\sim 15\%$. At $9^\circ \pm 2^\circ$ to the beam incidence, we measured 25% energy resolution with 10 GeV electrons. The light yield was determined to be 5.5 pe/GeV. The pulse risetime was ~ 5 ns with FWHM about 10 ns with the same beam conditions.

Conclusions

We tested seven projective hadron calorimeter towers constructed with laminated copper and scintillating fibers in the A3 test beam at BNL. The fitted energy resolution was $91\%/\sqrt{E}$ at 10 GeV pions with no correction for lateral shower leakage and fiber attenuation length (Fig. 22). The pions show a uniform response

across the boundaries of the modules and with respect to the incident angle between the fiber axis and the particle track. We measured e/π ratio of 1.08 ± 0.02 for pion energies between 10 to 20 GeV before any corrections.

SBC Activities

Introduction

The University of Iowa group concentrated SSC-related efforts on the Scintillating Barrel Calorimeter (SBC) subsystem of GEM last year. The main thrust of our SSC research has been twofold.

1. The R&D of the calibration and monitoring systems for the entire SBC subsystem. This includes the overall absolute and relative calibrations of the detector.
2. The R&D of the photodetection devices with their associated electronics, i.e., conventional photomultiplier tubes (PMT + bases), position-sensitive photomultiplier tubes (PSPMTs) and other devices that may be suitable for this detector. This also includes establishing quality control and assurance criteria for these devices.

In addition to the above mentioned major tasks, we are contributing in the following efforts of the SBC group which also includes the TTR and FNAL tests;

3. the selection of the clear transport fibers that are planned to be used for transporting light from the scintillating tiles to the light mixers and to the PMTs,
4. the spectral matching of the wavelength shifting (WLS) fibers to the scintillating tiles and spectral optimization of the PMTs to the entire assembly,
5. and the use of PSPMTs for a possible muon track identification with position measurement in the azimuthal angle by implementing a light division technique.

1. *SBC Calibration and Monitoring R&D*

Our initial studies in this subject are summarized in a GEM Technical Note (TN-92-184). Although at the time, we were envisaging a system for a fully contained scintillating fiber hadronic calorimeter, the basic principles remain unaltered for SBC. SBC is a $\sim 4.5\lambda_I$ deep hadronic calorimeter positioned behind a $\sim 6.5\lambda_I$ liquid argon hadronic calorimeter. This arrangement, as expected, makes SBC calibration and monitoring requirements considerably less demanding compared to the requirements that were once considered for a full scintillating fiber hadronic calorimeter. We have been investigating several options for calibration and monitoring. Among the several possible candidates for relative calibration and monitoring techniques for SBC, tunable pulsed lasers LEDs, and radioactive sources are considered.

A conceptual design for a pulsed N_2 pumped dye laser based system is shown in Figure 23. The advantage of this system is twofold. First, one can monitor the individual PMTs for gain and stability by selecting a dye (e.g., Coumarin 540A) at the peak spectral sensitivity of the PMTs, and second, one can excite the scintillator tiles by yet again selecting a wavelength via clear transport fiber (using another dye, e.g., Coumarin 440 for Y-7 absorption line), that is matched with the absorption spectrum of the SCSN-38-Y7 scintillating tiles. This idea is currently being tested at Iowa. One of the features of this technique, aside from the wavelength selection, is the number of photons that can be delivered to individual channels. The N_2 pumped dye laser we are currently using delivers 1.45 mJ at 337.1 nm per pulse. At 500 nm the power is reduced to 220 μ J per pulse. This is plenty of energy per pulse. If we require 10^6 p.e./channel, when we fold in the PMT quantum efficiency (Q.E.), light capture, losses at the optical joints, number of channels and the geometrical acceptance, the number of photons necessary turns out to be about 10^{11} photons. With the present setup we can deliver $\sim 4 \times 10^{14}$ photons at 450 nm.

One of the main difficulties with the light sources is its equal distribution to individual channels. As one expects it is considerably more demanding when one has a large number of channels. Moreover, each channel needs to receive a large and equal number of photons in order to be able to calibrate satisfactorily. Somewhat

connected to the above study we constructed a simple prototype for LED light distribution. Figures 24 and 25 show a light distribution that can be achieved by a relatively simple system. In this case, six LEDs (HPLM 3950) were embedded into a square (1×1 inch sq. $5 \frac{3}{8}$ " long) lucite light mixer and at the other end an optical coupling was made to 314 clear 1 mm diameter fibers. The distribution shows a spread of $\sim 20\%$ around the mean value. This was done without any optimization. We will continue to investigate this problem both using Monte-Carlo techniques and prototypes and reduce the spread by at least a factor of 5.

Although the use of natural radioactive sources is a attractive idea for calibration and monitoring and it has been implemented successfully by a number of large experiments, in the case of SBC however, it presents several technical problems. The conventional method has been to guide a radioactive source of several milliCuries (e.g., 4 mCi Co^{60} for UA4, 2 mCi Co^{60} for ZEUS, 3 mCi Cs^{137} for CDF, etc.) in a thin-walled stainless steel tubing which makes its rounds in the detector and at the same time to measure the DC current for each element. The present design does not easily accommodate this approach due to arrangement of tiles and mechanical construction details. One idea is to make use of the neutron activation of the absorber material due to abundant thermal neutrons in the SSC environment. If we consider that the final absorber material is Cartridge Brass (CDA Copper Alloy N0 C 260 00) then we have 70% Cu, 30% Zn with less than a percent other impurities. After a few hours of SSC operation, we expect to form short-lived beta emitters of a few of μCi 's per average size tile (Cu^{62} , Cu^{64} and Cu^{66}) in addition to the 0.511 MeV annihilation γ peak. After a few years of operation, we will have gamma sources of sufficient activity to be possibly useful for calibration (Zn^{64} and Cu^{60}). Although this idea is untried, we feel that it is worthwhile to perform initial tests for copper, cartridge brass, naval brass, and SEA 70A brass using the existing Howitzer (Pu-Be neutron source) at Iowa. For SBC a relatively low neutron rate ($10^2 - 10^3 \text{ n/cm}^2/\text{sec}$) may possibly render this technique inadequate, however, this very idea can be exploited for forward quartz calorimeter where neutron rates are higher ($10^5 - 10^6 \text{ n/cm}^2/\text{sec}$).

One of the ways of in situ absolute calibration is planned to be the use of single muons, as is the case is for the Muon and Magnet systems. At $\mathcal{L} \approx 10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$, single muon rate of $p_t > 15 \text{ GeV}/c$ per hour is about 17,000 for $0 \leq \eta \leq 1.28$. Another channel of dimuons is $Z^0 \rightarrow \mu^+ \mu^-$ with the rate of a few Hertz. We are in the process of documenting the results our studies for absolute calibration techniques which includes procedural and calculational methods.

2. Photodetector R&D for SBC

There are several objectives that need to be achieved when we consider the most suitable photodetector for SBC. These are mainly

1. high quantum efficiency (Q.E. $\geq 15\%$ at 520 nm),
2. moderately high gain ($\sim 5 \times 10^4$),
3. stable operation in high magnetic field of 0.8 T,
4. $< 4 \text{ ns}$ (10 mA into 50Ω load) rise-time,
5. $< 6 \text{ ns}$ fall-time,
6. $< 12 \text{ ns}$ width at baseline,
7. $< 1\%$ /month shift in stability and
8. appropriate mechanical dimensions and properties.

A natural and perhaps the safest selection for this task is conventional PMT. However, optimization is still necessary. On top of the standard requirements we need to concentrate on the high Q.E. in the green region and the operation in high magnetic fields. The commercially existing PMTs that are insensitive to high magnetic fields unfortunately are not green-extended (baseline choice for SBC is one such PMT, Hamamatsu R2490-05 fine-mesh PMT). Conversely, the green-extended PMTs do not perform well in high magnetic fields (e.g., Philips XP3461B was used for Cu/SciFi hadronic calorimeter test at BNL in 1992 for its green-extended characteristics). Our aim is to try to put these two criteria together as much as possible. We have already setup a system with a goniometer to study high magnetic field effects on the electron avalanche in the dynode (fine-mesh) systems of PMTs. What we know today is that this is not a technological difficulty but it has its roots in the

market forces and shares by the large manufacturers. We also intend to continue developing the criteria for quality control (QC), quality assurance (QA) and pricing for the photodevices and the associated electronics components.

3. *Tile + WLSFiber + PMT Spectral Matching, PSPMTs, and Light Division*

The spectral matching of the scintillating tiles, WLS fibers and the PMTs is a very crucial problem. According to Monte-Carlo studies, the number of photoelectrons for a 4-layer tower with 2 glued 1 mm diameter WLS fibers is about 50 for a *mip* with the existing SBC design. In order to investigate this problem and a possible implementation of extracting position information for single muons we constructed a prototype as shown schematically in Figure 26. In addition to attempting to optimize the spectral matching, effort was concentrated to read each fiber individually and to digitize it. The objective is to get positional information by interpolating the digitized information, possibly in the hardware level. Thus far preliminary analysis of data indicates ≤ 1 cm position resolution with the existing prototype. Figure 27 shows the on-line correlation between the two individual fibers for one of the runs. This is an ongoing project that requires considerable care and detailed analysis. We intend to proceed with this as far as we can with a possible implementation of a PSPMT. This will efficiently reduce the number of required channels (multiplex) and make the entire assembly hopefully more compact. This approach also connects with our project at CERN RD17 (FAROS) which focuses on the application of PSPMTs with scintillating fibers as a topological trigger device for LHC/SSC.

4. *Summary*

In the sections above we have outlined our past and future intentions for SBC related work for GEM. We have considered several options for calibration and monitoring of SBC. We have also studied the requirements for photodection. Several questions that remain can only be answered to satisfaction by continuous lab work. This mainly entails making prototypes, testing them, improving them

and testing them again with the aid of Monte-Carlo studies. And this is exactly what we propose and intend to do.

We will concentrate on the monitoring and calibration with lasers and LEDs as outlined. We will test the idea of calibration with the neutron activated radioisotopes. The proof of this technique depends entirely on lab work that we are performing now. The optimization of PMTs require clarification of performance parameters. These parameters evolve as we make headway with the design and tests of other components of SBC. The implementation of PSPMTs and/or light division techniques are in their early stages. The extent to which they will be successful and reliable will have to be seen in the near future.

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Figure 1 - Experimental set up for measurement of the space resolution. White circles in the SciFi array represent those fibers viewed by the R647 PMT (definition fibers).

connections (left) and the RTD circuit (right).

RD-17 Experimental Set-up

Figure 3 - Typical setup.

Figure 4 - Space resolution before unfolding the width of the definition fibers (0.5 mm ϕ).

Figure 5 - Linearity of the reconstructed position.

Figure 6 - Raw detection efficiency measured with the last dynode signals of the PSPM using leading edge and constant fraction discriminators.

Figure 7 - Internal time resolution. The two peaks were obtained by shifting the t_0 signal by 10 nanoseconds.

Figure 8 - Time sum ($t_L + t_R$) distribution obtained with the reference time t_0 defined by an external counter.

Figure 9 - An example of two-dimensional images obtained in real time with 2 planes of hodoscopes.

Figure 10 - "Type B" hodoscope showing the two movable layers.

Figure 11

Figure 12

(a) The signal after the delay line

(b) Last-stage node signal

Figure 13 Pulse shape of PSPM observed with Nagoya's SciFi array.

Prototype Fiber Calorimeter Tower

Figure 14. A single T-840 Pb/Fe/SciFi calorimeter tower.

BEFORE SOURCE CALIBRATION

AFTER SOURCE CALIBRATION

Figure 15. Comparison of the source scans before and after calibration.

Run 312: 50 GeV/c Mix C3C

Figure 16. 50 GeV mixed beam run. The parameter ξ effectively separates the electrons and hadrons [6].

Run 196: 50 GeV/c Mix C3C

Figure 17. 50 GeV mixed beam run. The same as the previous figure but the Cerenkov selection is applied [6].

Run 196: 50 GeV/c Mix C3C

Figure 18. 50 GeV mixed beam run. The parameter ζ is calculated to perform the particle identification [6].

Figure 19. The mean response, the sigma and energy resolution are calculated for 2 mm^2 regions along with the number of events per square in the lower right for Run 312 [7].

Figure 20. Scan through a crack with a mixed beam. The top figure is the sum of the lower two scans which correspond to the response from either side of the crack in the calorimeter module [7].

Figure 21 - The response of the calorimeter to 5, 10, 15 and 20 GeV/c single pions.

Figure 22 - The energy resolution measured by the copper/scintillating fiber calorimeter for single pions. No fiber light attenuation or lateral shower leakage effects are included. The curves represent the raw (dashed) and fitted (solid) energy resolutions. The dash-dotted line shows the energy resolution of $90\%/\sqrt{E} + 1\%$.

Figure 23

Figure 24

Figure 25

Figure 26

Figure 27

Remarks and Conclusions

Request for a Postdoctoral Fellow

The additions of a postdoctoral fellow for our tasks and a commensurate increase in our budget will ensure that our group continues to be significantly effective. This will give us the needed capability and support for our present physics program and our SSC detector R&D program and design, simulation, and construction work for the GEM detector. We are presently involved in E-704 (analysis) and in E-683 (analysis) at Fermilab. We will also contribute strongly to the preparation of the E-781 detector (fixed-target run at FNAL 1995) by providing and refurbishing six drift chambers and four MPWC. We hope that a person with a few years experience beyond the Ph.D. will take a central role in the SSC detector R&D being performed by the University group (GEM external calorimetry, scintillating barrel, and forward Hadron calorimetry) and provide the opportunity for the University of Iowa group to be more effective in the GEM collaboration and to be more compatible with respect to the large, well-established University groups and national labs in our collaboration.

Conclusions

The present task of Yasar Onel (Hadronic Interactions at Fermilab) started in November 1986 at the University of Texas at Austin. The progress of the group of hadronic interactions can be summarized as:

1. E-704

- running and analysis of CNI measurements (test run 1988)
- improvements on new CNI measurements
- new trigger
- new LED system
- on-line system using Iowa Vaxstation 3200

- CNI measurements (run period 1990)
 - CNI measurements analysis
 - installation of three large MWPC Iowa in the forward spectrometer
 - $p \uparrow p \rightarrow \Lambda(\Sigma^0)X$ run is completed
 - data analysis of above has started
 - main run of E-704 is completed
 - five publications from the analysis of the main run are published in journals
 - CNI-[Iowa task] is published in *Phys. Rev. Lett.* and *Phys. Rev. D*
 - two Ph.D. theses work.
2. E-683
- construction of six drift chambers
 - construction of a permanent test facility for wire chambers at Lab 6, Fermilab
 - chambers installed and fully operational in the Wide Band
 - engineering run of E-683
 - main run of E-683, June 1991 (start) – February 1992 (end)
 - data analysis has started
 - one Ph.D.
 - two papers are submitted to journals.
3. SSC R&D and GEM
- scintillating fiber based Calorimetry research
 - T-840 run at Fermilab
 - BNL 92 New Hadronic modules tests
 - Took Main responsibility for running the experiment, analysis of the data, and providing DAQ system for T-840
 - Took Main responsibility for designing a new DAQ system, running the experiment and providing New PMT's, bases for the New Hadron modules
 - RD17 at CERN, Ultrafast readout of Scintillating fibers: Running the experiment and analysis of the results

- GEM external calorimetry group [SBC, Forward Hadron Calorimetry] coordinator for read-out system with PMT and monitoring and calibration systems
- two M.Sc. theses.

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