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The Structure of the Nucleon and its Excited States

Progress Report

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DISCLAIMER

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I. Introduction

The past year has been an exciting and productive one for particle physics research at Abilene Christian University. The thrust of our experimental investigations is the study of the nucleon and its excited states. Laboratories where these investigations are presently being conducted are the AGS at Brookhaven, Fermilab and LAMPF. Some analysis of the data for experiments at the Petersburg Nuclear Physics Institute (Gatchina, Russia) is still in progress.

Scheduling of activities at different laboratories inevitably leads to occasional conflicts. This likelihood is increased by the present budget uncertainties at the laboratories that make long-term scheduling difficult. For the most part, the investigators have been able to avoid such conflicts. Only one experiment received beam time in 1994 (E890 at the AGS). The situation for 1995-1996 also appears manageable at this point. E890 and another AGS experiment (E909) will run through May, 1995. E1178 at LAMPF is presently scheduled for August/September 1995. E866 at Fermilab is scheduled to start in Spring/Summer 1996.

Undergraduate student involvement has been a key element in this research contract since its inception. Summer students participated at all of the above laboratories in 1994 and the same is planned in 1995.

A transition to greater involvement by graduate students will provide cohesiveness to ACU involvement at a given laboratory and full-time on-site involvement in the longer running experiments at FNAL and BNL. Funds to support a full-time graduate student are requested this year.

Finally, collaboration by Russian, Croatian and Bosnian scientists has proven to be mutually beneficial to these experimental programs and to the overall programs at the institutions involved. Past support has been augmented by other grants from government agencies and from the Research Council at Abilene Christian University. Additional funds are requested in this renewal to enable more programmatic support for these efforts, so that long-range plans can be made to carry out the experiments and to perform the analysis.

Highlights of the progress in this experimental effort since the 1994 progress report include:

- Assuming significant responsibility in the setup and running of Experiment 890 at the Brookhaven AGS. E890 is a measurement of charge symmetry by measuring the ratio of cross sections for $\pi^+d \rightarrow \eta pp$ to that for $\pi^-p \rightarrow \eta nn$. This ratio is sensitive to π^o-η mixing. Three ACU students (Jake Caire, Tomohiro Moriwaki and David

Rigsby) participated at BNL during Summer 1994, with Moriwaki electing to continue with the collaboration by enrolling in graduate school at UCLA. The main graduate student on the experiment, Aljosa Marusic, is presently supported by UCLA but was initially involved in this effort through the cooperative research effort between ACU and Rudjer Boskovic Institute (Zagreb, Croatia).

- Partial support from this grant has been provided to PNPI scientists (Nikolai Kozlenko and Vladimir Abaev). This involvement has had significant impact on both the running and the analysis of E890 and in the preparation of a proposal to move the SLAC Crystal Ball to Brookhaven.
- Successful runs using the Neutral Meson Spectrometer (NMS) for LAMPF Exp. 1268, $\pi^- p \rightarrow \pi^o n$ Cross Sections in the Region of the Δ Resonance (M. Sadler, spokesperson) were completed in 1992 and 1993. Data analysis is being done by Linh Nguyen at the University of Maryland as part of her Ph.D. thesis. This experiment was the first to use the NMS in the normal two-arm coincidence mode and BGO converters. This experiment culminated an involvement over three years by ACU faculty and students with LAMPF and other universities. The involvement of PNPI scientists (Sergei Kruglov and Nikolai Kozlenko), made possible by this grant, was particularly beneficial to the running of this experiment. Mark Whitton, a research physicist who has been involved with the NMS since its inception, was supported for two months from this contract last summer.
- Two Croatian scientists, Ivan Supek and Aljosa Marusic, from Rudjer Boskovic Institute participated in E1268 despite the tenuous political situation in former Yugoslavia. Future collaboration with RBI in Zagreb is anticipated through a joint U.S.-Croatia grant for collaborative science between the countries.
- Jimmy Redmon (former ACU undergraduate) completed his Master's degree at Texas Tech University, using as his thesis project the modelling of the π° Spectrometer and analysis of the 90° data for Exp. 882, measurement of differential cross sections for $\pi^- p \rightarrow \pi^o n$ at 10, 20 and 40 MeV. In an agreement with Texas Tech, Sadler was appointed an adjunct member of the graduate faculty at Texas Tech in order to supervise graduate theses. Isenhower also served as a member of Redmon's committee. Redmon and another student, Andrew Rose, spent the summer at Los Alamos, primarily working on the GEANT simulation of the π° Spectrometer and NMS.
- The collaboration between Petersburg Nuclear Physics Institute (PNPI), UCLA and ACU to measure cross sections for η production has continued. Scientists from PNPI participated in special runs to measure $\pi^- p \rightarrow \eta n$ using neutron

detectors at Brookhaven in 1994. A week of beam time to continue this work, with an emphasis on an independent technique for calibrating channel momentum, is being planned in 1995. This work is a continuation of measurements started in Gatchina in 1991.

- Fermilab Experiment 789 (J.C. Peng, LANL and D.H. Kaplan, IIT, spokes-persons) analysis has continued. Completion of data collection was in January, 1992. The first measurement of the cross section for b-quark production at 800 GeV/c has been submitted for publication . In addition, papers have been published in 1994 on upper limits for the decay $D^o \rightarrow \mu^+\mu^-$, the production of the J/ψ meson at large x_F, and nuclear dependence neutral-D-Meson production by 800 GeV/c protons on gold and beryllium targets. Data analysis is continuing at LANL, FNAL, ACU and U.C.-Berkeley. In particular, the di-hadron data sample has not been fully studied and will likely become the thesis project of a U.C. Berkeley student. E789 has shown that it is possible to record B° meson events with a fixed-target apparatus. The results of this experiment are elaborated on in Section III of this report.
- ACU hosted the E789 collaboration meeting in February 1994 which was attended by representatives of all of the collaborating institutions except Taiwan.
- The recommissioning of the E772/E789 spectrometer at Fermilab for Experiment 866 was begun in 1994. ACU students (undergraduates Josh Bush, Josh Willis and Derek Wise and graduate student Rusty Towell) played a significant role in refurbishing the hodoscope planes and recabling the detector (the detector was uncabled unnecessarily due to a wrong conclusion of the Tiger Team at FNAL). E866 will measure the anti-u and anti-d quark content of the proton using the Drell-Yan process. This experiment will build on Fermilab E772 which first measured the nuclear A-dependence of J/ψ and ψ' production. This experiment will have the advantages of the improved E789 data acquisition system which will allow for much higher data rates than that of E772. Several other proposals are being considered to extend E866 for the full length of the next fixed-target run at FNAL. ACU plans to participate in these measurements.
- ACU undergraduate students have continued to make valuable contributions to this research effort, particularly in preparing for the experiments at BNL and FNAL. Students serve as system managers on our research computers (a Vax 3600 and a DECstation 5000/200 that runs Ultrix), run and develop GEANT simulations, and perform specific analysis tasks (primarily with the PAW software from CERN).

Highlights of plans for the coming year include:

- Continued participation at Brookhaven in E890 and a new experiment (E909, Eta Production at Threshold in the Reactions $\pi^- p \rightarrow \eta n$ and $K^- p \rightarrow \eta\Lambda$). Data acquisition for both of these experiments should be completed during the 1995 AGS run that ends in May.
- Preparation of a BNL proposal for baryon spectroscopy using the SLAC Crystal Ball. We will propose to measure the reactions $\pi^- p \rightarrow \gamma n$, $\pi^- p \rightarrow \pi^\circ n$, $\pi^- p \rightarrow \eta n$ and $\pi^- p \rightarrow \pi^\circ\pi^\circ n$ at momenta from 0.4 to 1.9 GeV/c. A proposal was turned down last year to move the Crystal Ball (CB) to BNL to measure rare eta decays. Some reasons given were that the cost for transporting and upgrading the electronics for the CB were too large for one experiment and that the collaboration was not large enough for this project. Sadler will write the proposal and will serve as co-spokesperson (with W. B. Tippens of UCLA).
- Preparation of a letter of intent and, eventually, a proposal for hyperon spectroscopy at the AGS. Again the Crystal Ball will be used to measure full angular distributions of $K^- p$ interactions leading to Λ or Σ° plus γ, π°, η or $\pi^\circ\pi^\circ$ final states. Isenhower will serve as co-spokesperson for the proposal (with B. M. K. Nefkens of UCLA, A. Efendiev of JINR and N. Kozlenko of PNPI).
- ACU will supervise 3-4 students in the summer (1995) at FNAL to finish work on the hodoscopes and recable the detector for E866. Tasks of this type are ideally suited for undergraduates, in that they make a genuine contribution to the experiment, learn the 'nuts and bolts' of the apparatus, and use this knowledge to contribute at a higher level as their involvement with the experiment evolves. ACU has been able to make a very positive impact on experiments by providing manpower for such projects and plans to continue involving undergraduates in such activities.
- LAMPF Experiment 1178 is currently scheduled to start in August 1995 and ACU will provide student help to set up the NMS in the LEP channel and run the experiment. Anticipated tasks include moving and installing the NMS at LEP, including hook-up to the computer and testing; development of the dilution refrigerator and demonstration of successful operation; installation of the refrigerator, support structures, and target in LEP; and participating in the data acquisition.

II. Brookhaven Program

ACU is actively collaborating in several programs at the Brookhaven AGS that presently involve groups from UCLA, BNL, LANL, George Washington University (GWU), Ruder Boskovic Institute (RBI), Petersburg Nuclear Physics Institute (PNPI), and the Joint Institute for Nuclear Research (JINR in Dubna, Russia). Exp. 890, *A New Test of Charge Symmetry in Eta Production on Deuterium*, is presently underway and Exp. 909, *Eta Production at Threshold in the Reactions* $\pi^- p \rightarrow \eta n$ *and* $K^- p \rightarrow \eta \Lambda$, will start when E890 is completed. Both experiments are scheduled to be completed during the present AGS run cycle that is scheduled to end in May 1995. Another proposal, *Baryon Spectroscopy with the Crystal Ball*, is in preparation and will be defended at the April meeting of the BNL PAC. A Letter of Intent, *Hyperon Spectroscopy*, will also be submitted.

A. Brookhaven Exp. 890, *A New Test of Charge Symmetry in Eta Production on Deuterium*

ACU joined the E890 collaboration at the Brookhaven AGS in 1993. The spokespersons are B. M. K. Nefkens of UCLA, R. E. Chrien of Brookhaven and J. C. Peng of Los Alamos. Groups from UCLA, BNL, LANL, George Washington University, Jülich, Rudjer Boskovic Institute, Petersburg Nuclear Physics Institute, and the Joint Institute for Nuclear Research have participated in this experiment. As of this writing, the experiment is taking beam at the AGS and the data-taking phase is scheduled to be completed within weeks.

The test consists of a measurement of the ratio of the doubly differential cross section given by

$$R_\eta = \frac{d^2\sigma(\pi^+ d \rightarrow pp\eta)}{d^2\sigma(\pi^- d \rightarrow nn\eta)} .$$

Charge symmetry (CS) requires $R_\eta = 1.0$ for all incident pion energies and for every η production angle once minor adjustments have been made to compensate for the n-p mass splitting and for Coulomb interactions. The proposal is to measure R_η from threshold at $P_\pi = 607$ MeV/c to the maximum beam momentum (750 MeV/c) available in the C-8 channel at the AGS. This momentum range encompasses the S_{11} (1535)

resonance. The measurement of R_η is a direct test of the validity of charge symmetry in the unexplored domain of η-nuclear physics. Small violations of charge symmetry are expected as a consequence of differences in the nn and pp scattering lengths and the nnη and ppη coupling constants.

The ratio R_η is obtained by measuring the relative η yield due to π^+ and π^- and interactions in deuterium. The η is detected via its $\gamma\gamma$ decay mode using the η Spectrometer from Los Alamos. A floor layout is shown in Fig. 1. The device has been repaired and installed in the C-8 line of the AGS. The experience of the ACU investigators with similar spectrometers (the π^o Spectrometer and the NMS at LAMPF) has proven valuable in using the η Spectrometer, which was initially constructed for the threshold eta production measurements on nuclear targets at LAMPF (J. C. Peng, spokesperson).

The effects due to π^o-η mixing are expected to be largest near threshold and are of great interest. If an asymmetry is observed, i.e. $R_\eta \neq 1.0$, then further measurements of the ratio of the doubly differential cross section given by

$$R_\pi = \frac{d^2\sigma(\pi^+ d \rightarrow pp\pi^o)}{d^2\sigma(\pi^- d \rightarrow nn\pi^o)}$$

will be warranted. If $R_\eta \neq 1.0$ due to π^o-η mixing, then it is expected that $R_\pi \neq 1$, also. Measurement of this ratio was included in the original proposal and an attempt to measure it at least at one energy is planned. The opening angle of the two γ's from π° decay is much smaller than that from η decay, making it difficult to observe with the present support structure of the η Spectrometer. The Crystal Ball (described below) would be a natural detector to use for this measurement.

A secondary objective of this experiment is to explore the dependence on energy and angle of the $\pi^+ d \rightarrow pp\eta$ differential cross section. This reaction is being considered as the production reaction of a new AGS η factory. The η's could be tagged via the pp coincidence. New tests of C, CP, T, and CPT invariance can be done using various rare decays of the η.

A test run using a liquid deuterium target was conducted in July 1994 to set up the monitoring based on $\pi^\pm p \rightarrow \pi^\pm p$ and $\pi^\pm d \rightarrow \pi^\pm d$, to calibrate the η Spectrometer, to develop beam tunes, and to measure beam contaminations. Three ACU students, Jake Caire, Tomohiro Moriwaki and David Rigsby, spent the summer at Brookhaven working on the monitor detectors, participating in the run, and analyzing the data. In addition, support from this grant was provided to a Russian doctoral candidate, Nikolai Kozlenko, for both the summer run and the present run that began in January. The thesis student for the experiment, Aljosa Marusic from RBI, is presently being supported by UCLA but was initially brought to the collaboration through support from this grant. Finally, Moriwaki (who graduated in May 1994) elected to attend UCLA for graduate study and officially joined the UCLA collaboration during the summer.

The production run for this experiment started in January 1995. Sadler has participated in most of the running to date, made possible by a one-semester leave of absence granted by ACU.

The η spectrometer originally had a single converter plane (one radiation length of BGO followed by wire chambers) in front of the NaI calorimeter (4x4 array, each 4"x4"x16"). It was demonstrated in the Summer 1994 run that the calorimeters alone provide adequate invariant mass resolution to identify η production. This result is not surprising since the opening angle of the $\eta \rightarrow \gamma\gamma$ decay is large (~140°), so that the converter plane information did little to improve the invariant mass resolution. This relaxation of the trigger (not requiring a conversion in front of the NaI) increases the event rate by a factor of five. For this reason, it was elected to run in this mode and concentrate on quality measurements of R_η at several momenta from 660 to 750 MeV/c and cover a range of opening angles. If significant deviations from charge symmetry are found, then further running will be requested to concentrate on measurements of R_π, with conditions optimized for the smaller opening angles for the $\pi^\circ \rightarrow \gamma\gamma$ decay mode.

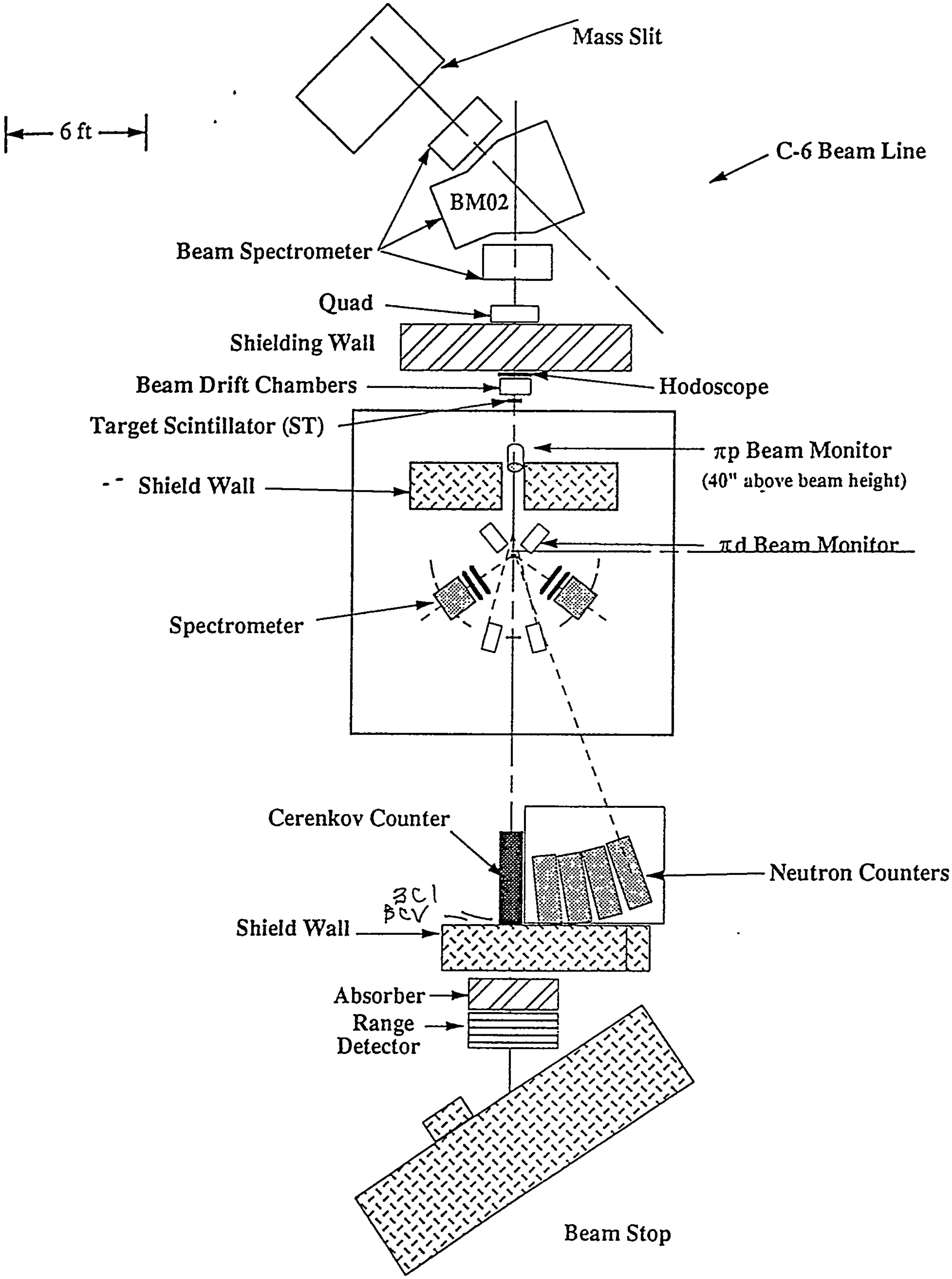
Examples of results from the summer run are shown in Fig. 2. The veto counters shown in Fig. 1 are not utilized by the event trigger but are used to select neutral events in the E_γ^R-versus-E_γ^L scatter plot in Fig. 2a. Both scales are in MeV. The reconstructed γ–γ invariant mass is shown in Fig 2b, after applying a cut of 240 MeV on each arm. The η peak is reconstructed with minimal background exhibiting a width of $\sigma = 33$ MeV/c^2 (6%).

An example of an online spectrum taken in February 1995 in Fig. 3 shows how a hyperbolic cut (corresponding to $E_\gamma^R * E_\gamma^L = [265 \text{ MeV}]^2$) also is an effective way of isolating η production. The spectrum in Fig. 3a is the same as Fig. 2a, but with poorer statistics. Fig. 3b shows the events surviving the single-arm energy cuts and the hyperbolic cut. Fig. 3c shows the invariant mass for all of the γ's in Fig. 3a, with the η peak riding on the tail of a continuum of γ rays arising from $2\pi^\circ$ decay. (Note that the η peak is a little to the left of the vertical line that corresponds to the η mass, but this is adjusted by a single factor in software that represents the calibration of pulse height in the NaI to the γ energy.) Fig. 3d shows the invariant mass spectrum for the events in Fig. 3b, demonstrating the excellent η signal we have in this experiment.

Two neutron counters from UCLA (the same design as for the PNPI program) were also installed for the test run. These counters were used to investigate the feasibility of measuring $\pi^- p \rightarrow \eta n$ near threshold at the AGS. The C-8 line offers two attractive features for this measurement compared to PNPI. These are an increase of over a hundred in π^- beam intensity and the ability to determine the momentum of an individual pion to within ±0.3%. Preliminary results during the test run indicate that the backgrounds at the AGS are significantly higher than at PNPI and better shielding will be needed. The counters were mounted in a similar fashion to the PNPI measurement, at 4-6° and 5 m downstream from the target. Significant background was identified from the downstream beam hitting the shielding wall. Shielding will be added before the 1994 run to reduce this background.

Three ACU undergraduates (Jake Caire, Tomohiro Moriwaki and David Rigsby) participated in the staging of the experiment and in the test run during the summer. Tasks included writing subroutines for on-line analysis in the data acquisition code; preparing, repairing and mounting scintillation counters used for the beam trigger, beam veto, spectrometer veto and cosmic trigger; and modelling the beam transport properties of the modified C8 beam line, particularly to determine the optimum location to place a 0.3-cm lead radiator upstream of the last dipole in order to reduce the electron contamination in the beam.

A Russian physicist, Nikolai Kozlenko from PNPI, was partially supported from this grant to participate in E890 for four months last summer. Other support was obtained from the Research Council of Abilene Christian University. This renewal application requests funds to facilitate greater participation for Russian scientists as well as scientists from other foreign institutes. As demonstrated in the next section, such collaborations have proven extremely beneficial in our research program.



E890 Layout

Figure 1. Layout for Exp. 890 in the C8 line at the Brookhaven AGS

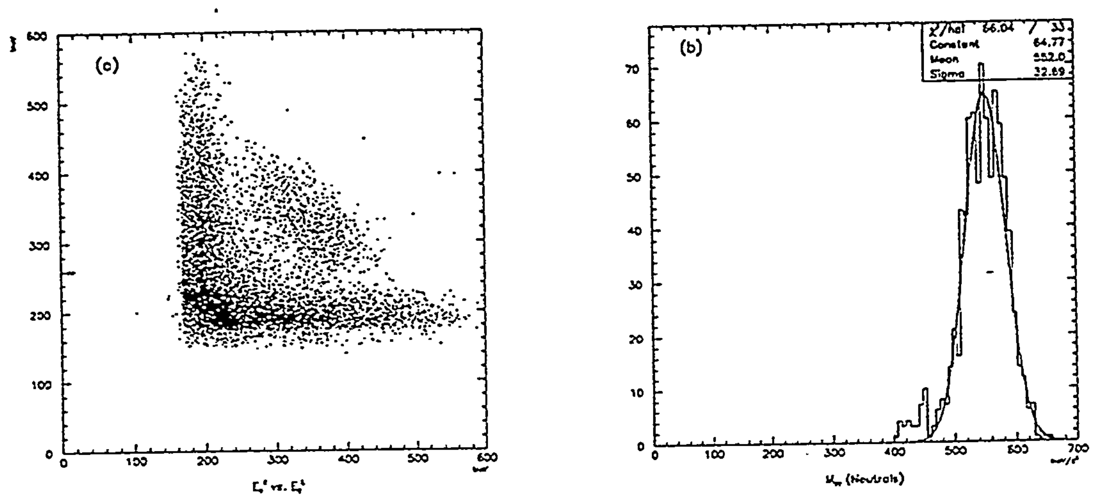


Figure 2. Data analysis from E890, showing clean separation of the η meson.

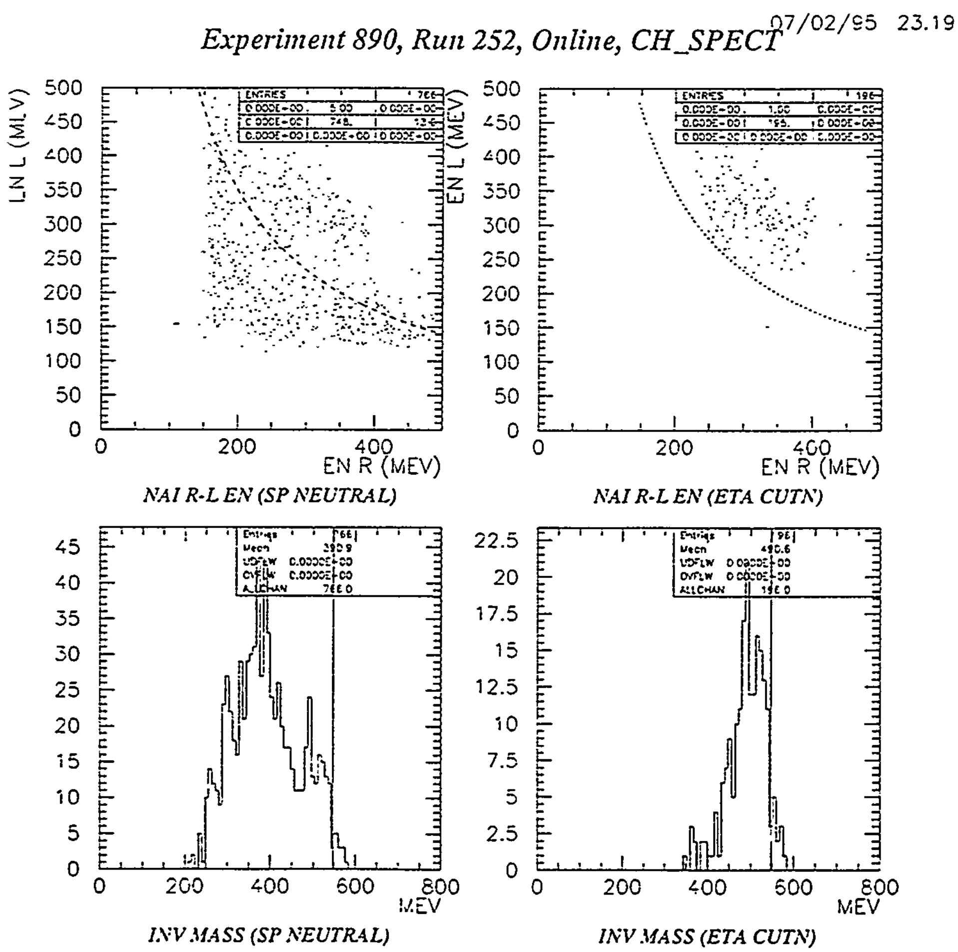


Figure 3. Online data (February '95) from E890, described in text.

B. Using Threshold η Production to Verify and to Calibrate Medium-Energy Beam Channels

A very interesting exercise was made possible through the utilization of one day of beam time at the conclusion of the E890 test run at Brookhaven last summer. Data were taken with the four neutron detectors shown in Fig. 1, using as a trigger

$$S_1 * S_T * \overline{BV} * \left[(N_1+N_2+N_3) * \overline{NV_1} + (N_4+N_5+N_6) * \overline{NV_2} + (N_7+N_8+N_9) * \overline{NV_3} + (N_{10}+N_{11}+N_{12}) * \overline{NV_4}\right].$$

S_1 (not shown in Fig. 1, but placed just after the mass slit) and S_T are the beam-defining counters, and $\overline{BV}$ (also not shown) was a beam veto counter placed downstream of the target. The neutron event (shown in brackets in the trigger) reflects the structure of the neutron detectors shown in Fig. 4. For example, $(N_1+N_2+N_3) * \overline{NV_1}$ is true if there is a signal above threshold in any of the three scintillators that comprise the first detector with no signal in the anti-counter, NV_1. Each detector consists of three blocks of BC-408 scintillator that are 25.4 cm deep, 25.4 cm high and 8.9 cm wide. Each scintillator is viewed by two photomultiplier tubes (as shown in Fig. 4). Each group of three scintillators was fronted by a single anti-counter, NV.

The identification of neutrons from various sources is accomplished by measuring the time-of-flight (TOF) difference over the distance from the interaction point in the target to the neutron counters. The angles and distances to the centers of the twelve scintillators are given in Table 1. A raw TOF spectrum for counter N_5 is shown in Fig. 5, taken at $p_\pi = 720$ MeV/c. The dominant peak toward the left of the spectrum is due γ rays from various sources. This peak is shifted so that the centroid is at channel 0 and becomes the time reference, called the 'γ flash'. The dominant process to the right (later time) of the γ flash is primarily due to neutrons from the $\pi^- p \rightarrow \pi^\circ \pi^\circ n$ reaction. The times for these neutrons are continuously distributed due to the three-body final state.

Both peaks riding on top of the $\pi^- p \rightarrow \pi^\circ \pi^\circ n$ background in Fig. 5 are due to neutrons from the reaction $\pi^- p \rightarrow \eta n$. Near threshold, the velocity of the cm frame is larger than the neutron velocity. Both forward- and backward-going neutrons (in the cm) are detected at the same forward angle in the laboratory. These neutrons have different velocities in the laboratory frame, hence different TOF's. The solid curve is an attempt to fit the η peaks with two Gaussians on top of an exponential background.

Counter	Angle	Distance
N_1	5.34°	374.1 cm
N_2	6.70°	374.0 cm
N_3	8.06°	374.1 cm
N_4	10.91°	374.8 cm
N_5	12.27°	374.7 cm
N_6	13.63°	374.8 cm
N_7	16.26°	375.2 cm
N_8	17.62°	375.1 cm
N_9	18.98°	375.2 cm
N_{10}	21.85°	375.4 cm
N_{11}	23.21°	375.3 cm
N_{12}	24.56°	375.4 cm

Table 1. Floor positions of the twelve individual neutron counters.

The widths of the η peaks in Fig. 5 are ~2-3 ns, with the dominant contribution coming from the momentum spread in the beam. Fig. 6 shows the data (again for N5) plotted in two dimensions with time (in ns) along the horizontal and the reconstructed beam momentum (in MeV/c) along the vertical axis. The parabolic curve is the kinematic prediction, assuming that the neutron goes to the center of the counter. The splotch plot of the data displays the enhancement around the kinematic locus of neutrons from $\pi^- p \rightarrow \eta n$ and demonstrates the origin of the two peaks (above threshold for this reaction at a fixed angle, there are two possible TOF's for a single momentum). The next step is to remove this contribution from the time spread by correcting for the measured beam momentum, obtained by the beam drift chambers before and after the last dipole. One way of accomplishing this is simply to calculate the missing mass,

$$\left[(E_{\pi^-}+m_p-E_n)^2-(\vec{p}_{\pi^-}-\vec{p}_n)^2\right]^{\frac{1}{2}}$$

where m_p is the proton mass, the energy and momentum of the π^- beam, E_{π^-} and p_{π^-}, are obtained from the beam tune (and the $\delta p/p$ value obtained from the beam drift chambers), and the neutron energy and momentum (E_n and p_n) are calculated from the TOF. The missing mass spectrum for N_5 is shown in Fig. 6. Now, η production appears as a <u>single</u> peak (at the mass of the η) that is quite sharp, with a width

(FWHM) of ~15 MeV/c^2. One has to be careful with this technique, however, because of the naturalness of sharp phenomena near threshold. The reason for this occurrence is shown kinematically in Fig. 7, which shows the TOF as a function of the missing mass for neutrons arising from $\pi^- p \to nX$, where X is the missing mass. Four curves are shown which correspond to the centers of the four neutron detectors. The TOF varies very slowly as a function of the missing mass until threshold is approached (all curves are calculated assuming the centroid beam momentum of 720 MeV/c). Near threshold a small change in missing mass covers a wide range in the TOF.

Another approach is to assume a missing mass equal to m_η, calculate the actual beam momentum from the measured TOF, and compare with the value determined from the beam chambers. The results of such an exercise are shown in Fig. 8, where the horizontal axis is $p_{calc} - p_{cham}$ and the vertical axis is the number of counts after subtracting the normalized background from the target empty run. The distribution peaks at 8 MeV/c, indicating that the actual beam momentum is ~1% higher than the nominal value. The other counters also exhibit a difference consistent with a 1% miscalibration of the channel momentum. More running is planned with the neutron counters in the present 1995 run in order to refine the technique and to try to decrease the backgrounds. A copy of the request is included below:

> As part of the US/Russia general program, "Fundamental properties of matter", two experiments are presently underway at BNL to investigate eta production. These are #890 (a measurement of $\pi^\pm d \to \eta NN$ to search for a violation of charge symmetry) and #909 (measurements of $\pi^- p \to \eta n$ and $K^- p \to \eta\Lambda$ to determine the η-baryon scattering lengths).
>
> In these experiments it is quite important (especially for #909) to know:
>
> 1). The absolute momentum of the beam, and
>
> 2). the precise reconstruction of the momentum of the individual pions as determined from the wire chamber information and the TRANSPORT matrix that characterizes the magnetic elements.
>
> For this purpose, PNPI and ACU have collaborated on a method for independent calibration of the beam momentum near the threshold for eta production. The technique uses the large UCLA scintillation counters to detect the neutrons from $\pi^- p \to \eta n$. The sensitivity (on the order of a few tenths of a percent) to the absolute momentum calibration was first demonstrated in experiments at PNPI in 1992-93, where cross sections

for $\pi^- p \rightarrow \eta n$ were measured from 690 to 740 MeV/c.

The incorporation of beam wire chambers in the C8 line at BNL for E890 provides, in principle, the momentum of the individual scattered pions by measuring the X position before the last dipole and the full trajectory (X, θ_X, Y, θ_Y) after the last quadrupole. The inverse matrix from TRANSPORT is used to calculate the beam momentum, taking into account the focusing from the last three quadrupoles. In a one-day run in Summer 94, it was shown that incorporating the simple kinematic correction for the expected TOF of the neutron based on the pion momentum resulted in a sharp peak for this observable.

We propose a separate seven-day run to develop this technique further in the C8 line at BNL, using the liquid hydrogen target and the neutron counters that are already in place. We think that we can improve the background conditions, as we installed halo veto counters (based on the analysis of last year's run) and plan to investigate other methods to decrease the number of background triggers.

A second goal of the proposed measurements is to observe the background rejection obtained by measuring the yield for $\pi^- p \rightarrow \eta n$ using the neutron counters and one arm of the η Spectrometer in coincidence. Such measurements should provide cleaner signals for detecting all-neutral final states and provide insight on the technique to use neutron counters as a tag for neutral meson production. This measurement has been of common interest to the PNPI-ACU-UCLA collaboration since 1992.

As indicated in this request, the development of this technique dates back to our collaboration with PNPI at the Gatchina synchrotron, reported in the 1992-1994 progress reports. The measurements there were somewhat cruder (no wire chambers were used in the beam), but a similar 1% miscalibration in the central momentum of the beam channel was observed.

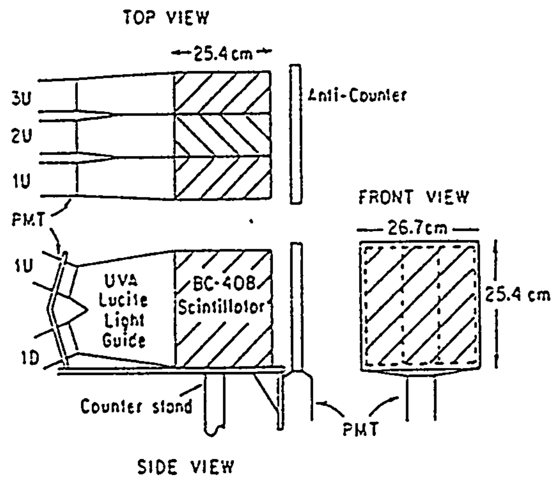


Figure 4. Three views of a complete neutron detector from NIM **A275**, 281 (1989).

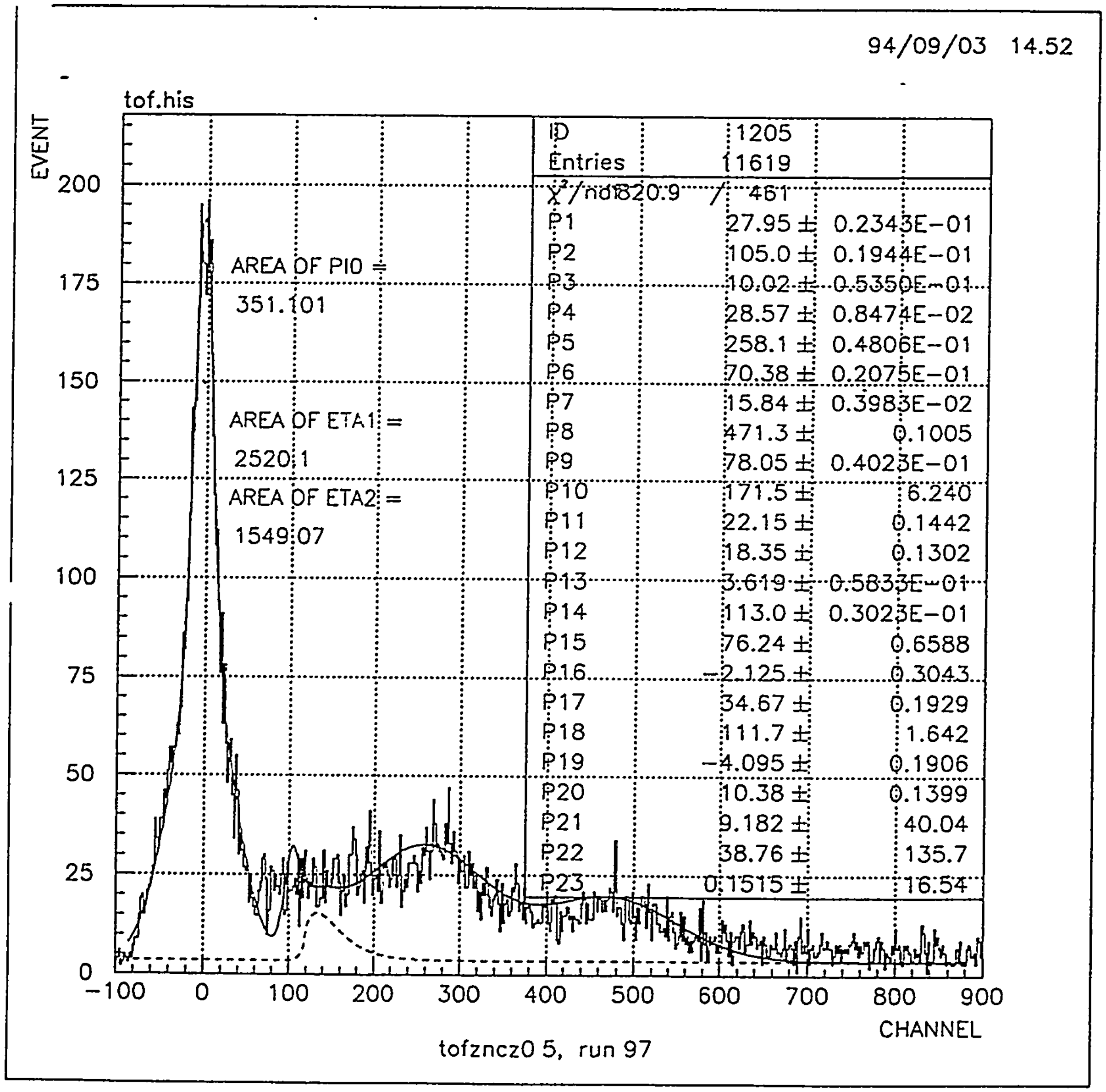


Figure 5. Neutron TOF measurements showing η production from $\pi^- p \rightarrow \eta n$.

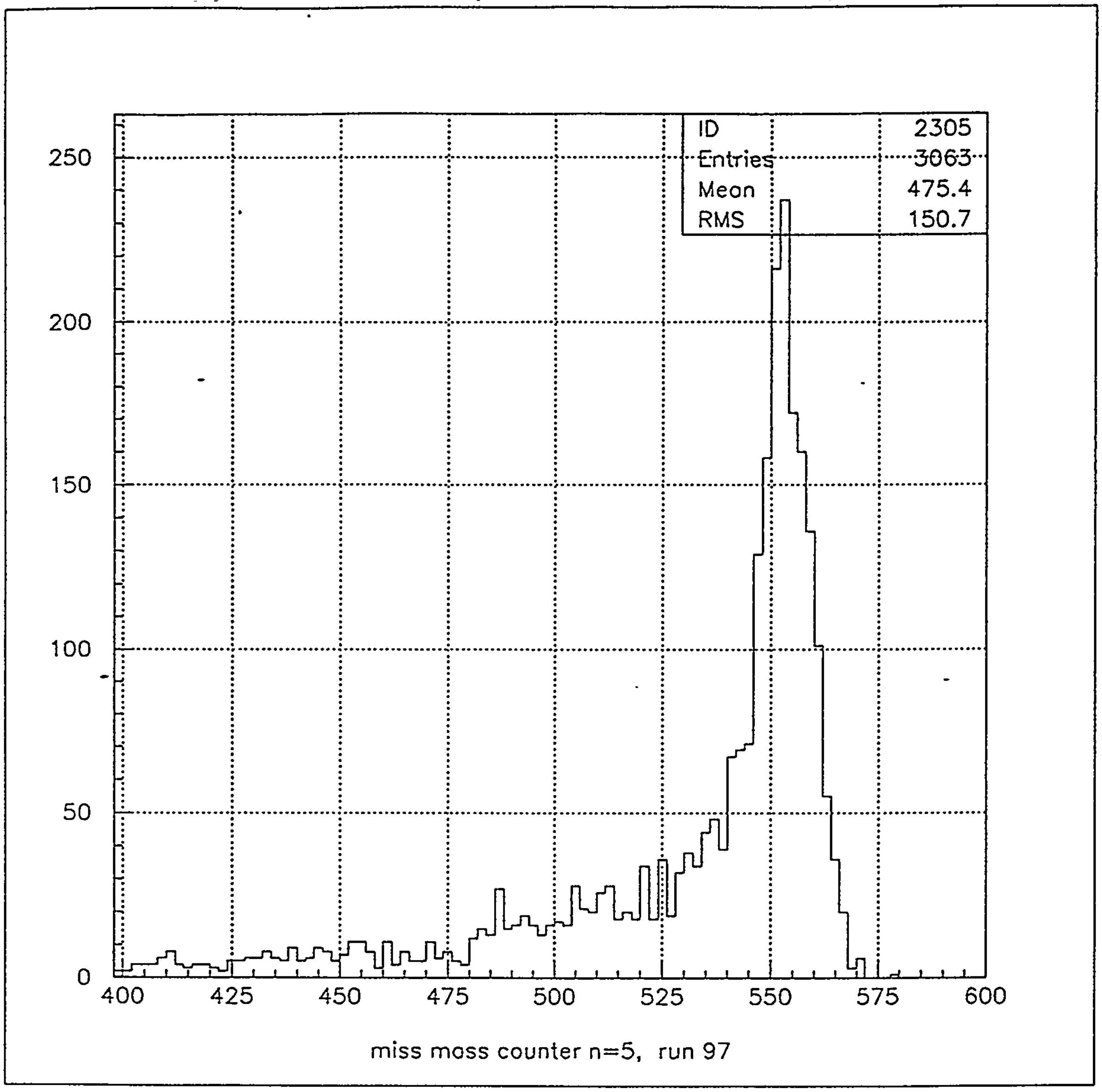


Figure 6. Missing mass distribution for counter N5.

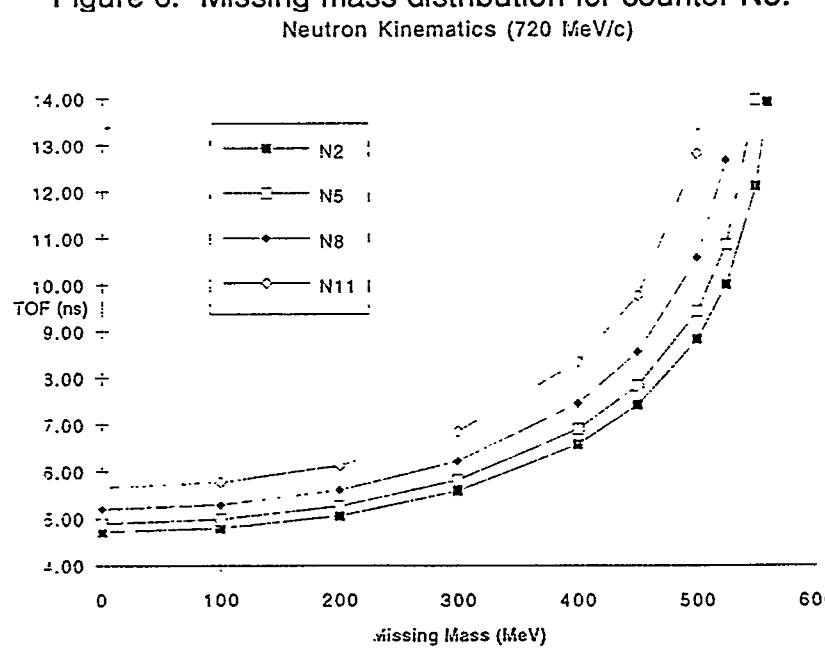


Figure 7. $\pi^- p \rightarrow \eta n$ kinematics showing TOF as a function of missing mass.

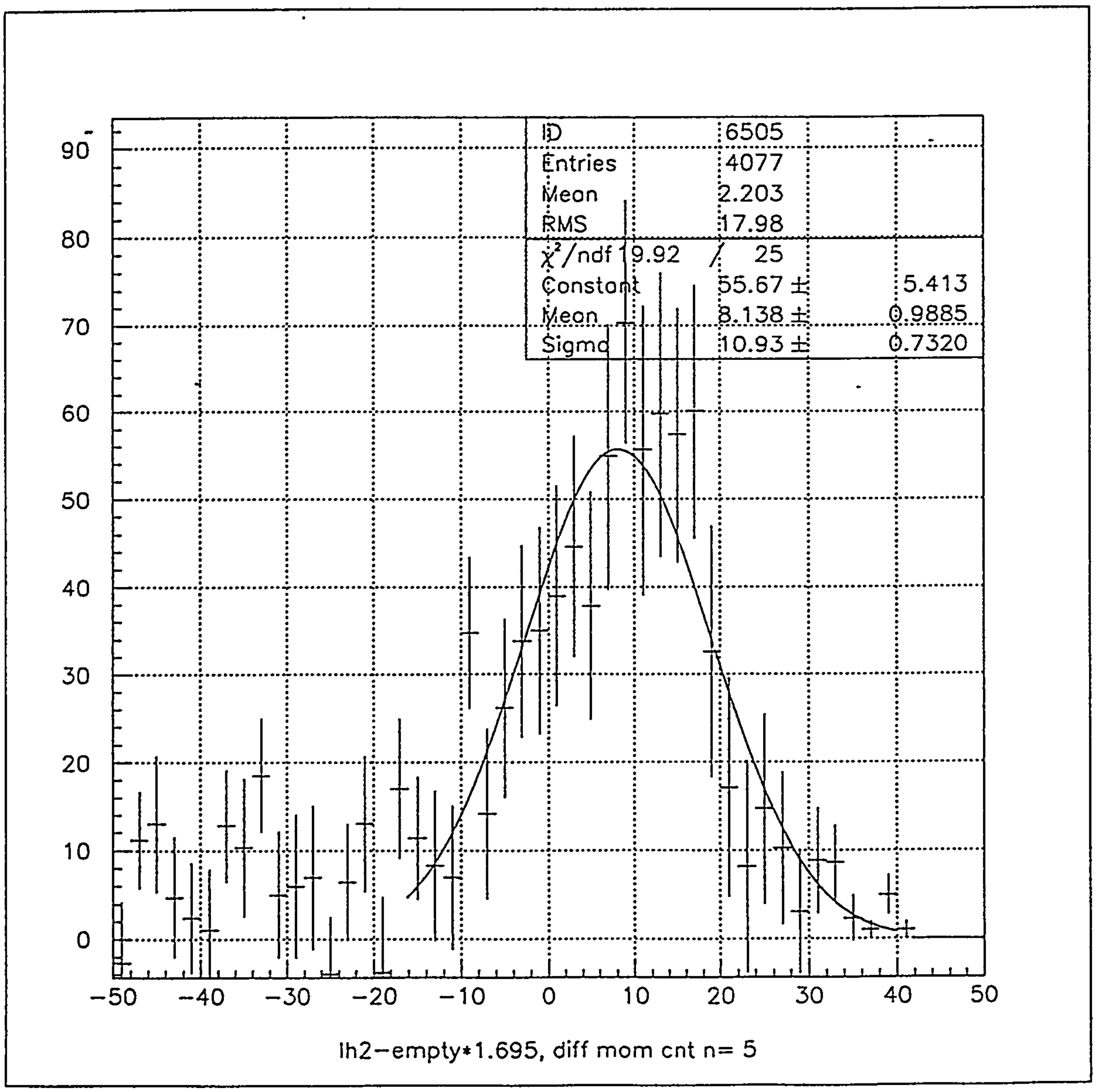


Figure 8. Event reconstruction calculating p_{beam} assuming missing mass = m_{η}.

C. Eta Production at Threshold in the Reactions $\pi^- p \to \eta n$ and $K^- p \to \eta\Lambda$

BNL experiment 909, η production at threshold in the reactions $\pi^- p \to \eta n$ and $K^- p \to \eta \Lambda$, was approved at the Fall 1994 meeting of the PAC to run immediately after the completion of Exp. 890. The spokespersons are W. J. Briscoe (George Washington University) and W. B. Tippens (UCLA). The other groups participating in the measurement are ACU, BNL, RBI, JINR and PNPI. The experiment will utilize the η Spectrometer presently being used for Exp. 890 (described above). The experiment was approved for 600 hours which should be available in April and May if the AGS runs according to the presently assumed schedule. As stated in the previous section, we hope to obtain an additional week of beam time to calibrate the momentum of the beam line using the neutron detectors. The absolute momentum calibration is crucial to these measurements at the threshold for η production. The logical time for the neutron TOF measurements would be between the two experiments, probably in late March.

The proposal is included below. The primary motivation for these measurements is to determine the η–n and η–Λ scattering lengths and to provide data for the reactions $\pi^- p \to \eta n$ and $K^- p \to \eta \Lambda$ in the vicinity of the S_{11} [N*(1535)] and $S_{01}[\Lambda^*(1670)]$ resonances. Present plans are to continue this experimental program in baryon spectroscopy with the Crystal Ball, as described in the next section.

AGS PROPOSAL 909

TITLE: **ETA Production at Threshold in the Reactions $\pi^- p \rightarrow \eta n$ and $K^- p \rightarrow \Lambda \eta$**

FROM: W.J. Briscoe, T. W. Morrison, Z. Papandreou, S. Philips,
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D. White - **UCLA**
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M.E. Sadler, L.D. Isenhower - **Abilene Christian University**
A. Marusic, I. Slaus - **Rudjer Boskovic Institute**
A. Efendiev - **JINR**, Dubna
V. Abaev, V. Bekrenev, N. Koslenko, S. Kruglov - **PNPI**, Gatchina

BEAM : 740 MeV/c, K^-, π^-
REACTIONS: $\pi^- p \rightarrow \eta n$, $K^- p \rightarrow \Lambda \eta$
TARGETS: LH_2
BEAMLINE: LESBII C-8
TIME REQUESTED: 600 hours

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Abstract

The threshold for η production in the reactions $\pi^- \, p \rightarrow \eta \, n$ and $K^- \, p \rightarrow \Lambda \, \eta$ is close to the mass of the $S_{11}(N^*(1535))$ and $S_{01}(\Lambda^*(1670))$ resonances, respectively. The cross section for η production in both reactions is unexpectedly large as are other η threshold production cross sections. Better quality data, particularly angular distributions which are currently lacking, in both the K^-p and π^-p reactions are needed to understand the role of these resonances near the η threshold. There is a factor of four discrepancy in the determination of the ηN scattering length and the $\eta\Lambda$ scattering length is unknown due to a lack of precise threshold cross section data. New, precision data at threshold would allow better determinations of these scattering lengths.

We propose to measure total cross sections as well as angular distributions for η production in both of these reactions from threshold (P_π = 685 MeV/c, and P_K = 723 MeV/c) up to 760 MeV/c. The η particles are detected via the 2γ decay mode using the improved η spectrometer currently in operation on the C-8 beamline. We are requesting 600 hours of total running time for these measurements.

1 Introduction

Over the last several years, there has been renewed interest by the nuclear physics community in the production of the η meson in the fundamental process (single nucleon) and in nuclei. The π - nucleon and π - nucleus interactions at intermediate energies have been extensively studied at meson factories, especially at LAMPF [1]. These measurements have led to a complete, non-ambiguous set of π-N scattering amplitudes [2]. The $\pi^-p \rightarrow \eta n$ reaction allows access to one of the most important quantities in eta-nuclear physics: the $\eta - N$ S-wave scattering length $a_{\eta N}$. Studying the interaction of heavier, strange mesons such as the kaon with the nucleon would broaden the scope of this program.

Eta meson production by π^- and K^- beams at low energy involves three remarkable baryon resonances, the $S_{11}(1535)$ associated with the reaction $\pi^-p \rightarrow \eta n$, the $\Lambda(1670)$ associated with $K^-p \rightarrow \eta\Lambda$, and at higher energies the $\Sigma(1750)$ associated with $K^-p \rightarrow \eta\Sigma$. All three of these resonances share the following properties summarized in Table 1 [3]: i) the mass or pole position is very close to the η production threshold; ii) the branching ratio to the η channel is much larger than one might naively expect based on simple phase space availability, e.g. BR($S_{11} \rightarrow N\eta$) exceeds by 40 - 60% the πN and the $\pi\pi N$ branching ratios whose phase space is much larger; and iii) the η production cross section is large, $\sigma(\pi^- p \rightarrow \eta n)$ being $\approx 6\%$ of $\sigma(\pi^- p \rightarrow all)$ and $\sigma(K^- p \rightarrow \eta\Lambda)$ being $\approx 3\%$ of $\sigma(K^- p \rightarrow all)$.

Table 1: Comparison of baryon resonances associated with η production.

PDT Symbol	I,J^P	Spectral Notation	η Decay Fraction(%)	Q (MeV)
N*(1535)	$\frac{1}{2}, \frac{1}{2}^-$	S_{11}	45-55	2 ± 16
Λ*(1670)	$0, \frac{1}{2}^-$	S_{01}	15-35	7 ± 5
Σ*(1750)	$1, \frac{1}{2}^-$	S_{21}	15-55	10 ± 20

There is some uncertainty in the exact pole position of the $S_{11}(1535)$. A recent study by Clajus and Nefkens [4], using a Breit-Wigner parameterization with energy-independent width, implies that resonance might be about 40 MeV lower than the PDG assigned value and coinciding with the η threshold. This is also in agreement with the recent results of Höhler [5] in the determination of πN pole parameters, see fig. 1. However, recent photoproduction data from Mainz and Bonn [6] indicate that the mass of the S_{11} is above the η threshold. Höhler [5] has argued that his speed plots indicate that the observed S_{11} is a combination of a resonance and cusp phenomenon due to the opening of the η channel. From his arguments, it appears clear that a reliable analysis of the S_{11} can only be performed after better quality $\pi^- p \rightarrow \eta n$ data have been taken near threshold. There is no corresponding speed plot for the $S_{01}(1670)$ because of the lack of data near threshold for $K^- p \rightarrow \eta\Lambda$.

It has been found experimentally in the last few years that η production in various hadronic processes is unexpectedly large, e.g. $\sigma(pp \rightarrow \eta pp) = 1\ \mu$b [7], $\sigma(np \rightarrow \eta np) \sim 7 \times \sigma(pp \rightarrow \eta pp)$ [8], $\sigma(np \rightarrow d\eta) \sim 0.2$ mb just above threshold [9], $\sigma_t(pd \rightarrow \eta^3He) = 0.4\mu$b 1.5 MeV above threshold [10], and $\sigma_t(dd \rightarrow \eta\alpha) = 10$ nb just above threshold [11]. If this is not due to the $S_{11}(1535)$ resonance, then the question remains why these cross sections are so large.

The existence of a quasi-bound, and especially a "bound", ηN system would contribute to explaining these processes. The $pd \rightarrow \eta\ {}^3He$ reaction has led Wilkin [12] to predict the existence of an η-mesic nucleus which can only exist when the ηN interaction is strong and attractive as opposed to the πN interaction which is weak

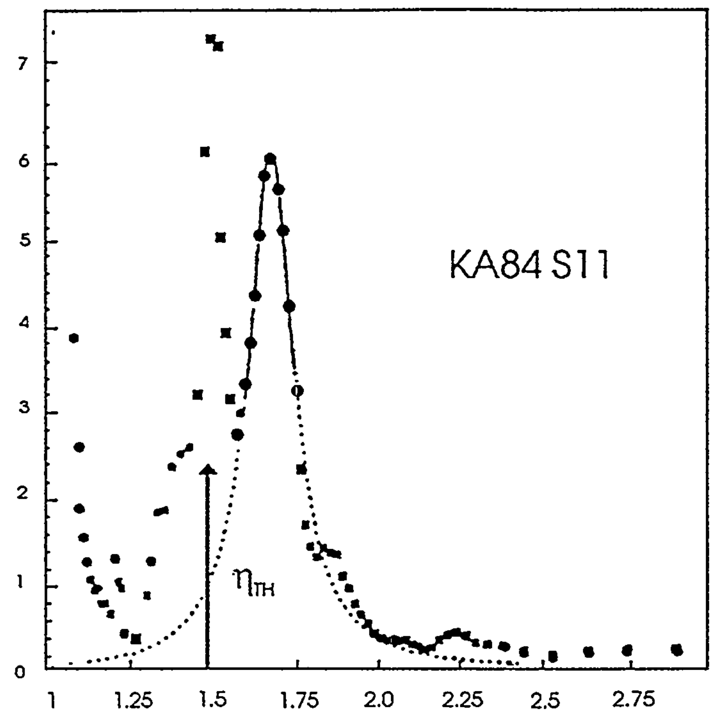

Figure 1: Speed plot for $S_{11}(1535)$, ref. [5]. A speed plot is the variation in the T-matrix amplitude as a function of CM energy (GeV).

and repulsive in the S state. While one would expect that a pseudoscalar meson is produced near threshold in an S-wave interaction, there is at least one exception in $pd \to \eta\, ^3He$. The η production cross section in the reaction $pd \to \eta\, ^3He$ certainly does not follow the typical S-wave shape, but rapidly achieves $0.4\mu b$ and remains constant for about 11 MeV above threshold [10]. An experiment submitted by several members of our collaboration has been approved at Saturne to make precise measurements of the absolute cross section of $pd \to \eta^3He$ in small energy steps very near threshold as well as over the full angular region [13]. Only the existence of these data near threshold can test Wilkin's prediction for $pd \to \eta\, ^3He$. Angular distributions of the cross section near threshold for $\pi^- p \to \eta n$ and $K^- p \to \eta\Lambda$ are also needed.

For the determination of the ηN and $\eta\Lambda$ scattering lengths, precise cross sections at threshold are needed. The present world data for $\pi^- p \to \eta\, n$ is shown in fig. 2. At threshold, the data is primarily that of Binnie *et al.* [14] and four other data points from Brown *et al.* [15], Bulos *et al.* [16], Deinet *et al.* [17], and Richards *et al.* [18]

These data have been carefully reviewed by Clajus and Nefkens [4]. All of the data except for Binnie and Bulos seem to have uncertainties in the knowledge of their beam momentum. The Binnie data are differential cross sections from which the total cross section has been extracted by assuming S-wave production. Thus, more precise data in this region including both total cross sections and angular distributions would help resolve these discrepancies.

2 Theoretical Motivation

One of the more common methods of determining the scattering length has been to extract the $\eta N \rightarrow \eta N$ t-matrix by solving the coupled channel system of $\pi N \rightarrow \pi N$, $\pi N \rightarrow \eta N$, and $\eta N \rightarrow \eta N$ simultaneously. Values for the scattering length , $a_{\eta N}$, quoted in the recent literature are: $a_{\eta N} = (0.55 \pm 0.2 + i0.3) fm$ by Wilkin [12], $a_{\eta N} = (0.98 + i0.37)$ fm by Arima *et al.* [19], and $a_{\eta N} = (0.27 + i0.22)$ fm by Bhalerao and Liu [20]. The uncertainty in these values are partly due to the lack of quality data for $\pi^- p \rightarrow \eta n$, see fig. 2.

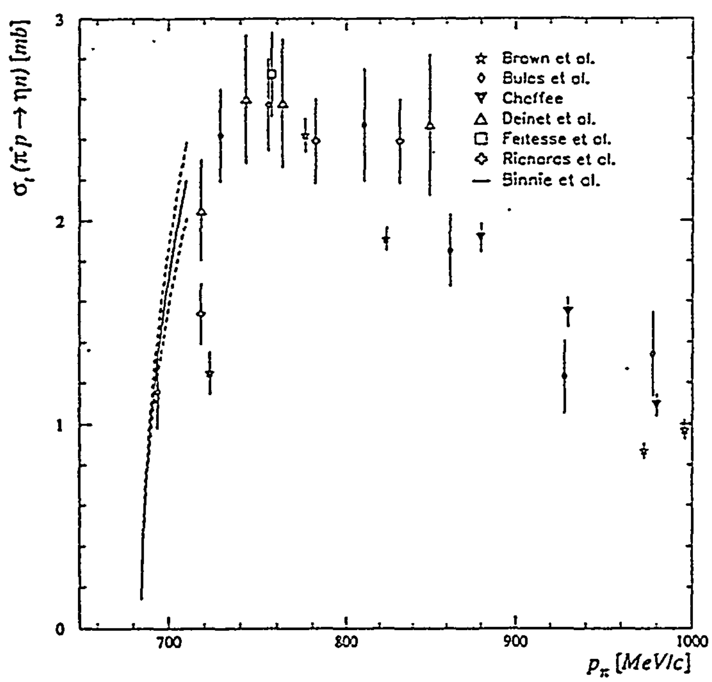

Figure 2: Existing world data for $\sigma(\pi^- p \rightarrow \eta\, n)$, ref. [4]

Obviously, the difference in the real part by almost a factor of four is unacceptable and does not permit a rigorous test of theoretical models. For example, the strongly attractive ηN-interaction may lead to a new kind of hadronic nuclear bound state, the

η-mesic nucleus, suggested by Wilkin [12] as a result of his analysis of the new UCLA-Saclay $\sigma(pd \rightarrow \eta\ ^3He)$ threshold data and the presently available $\sigma(\pi^- p \rightarrow \eta\ n)$ data. This analysis consists of removing the rapidly varying phase space factors and investigating the variation of the invariant amplitude squared as a function of the c.m. η momentum. The precise magnitude of $a_{\eta N}$ needs to be determined since the $Re(a_{\eta N}) \approx 0.50 fm$ would suggest a bound η-nuclear system for mass numbers as small as A=3, [12] while $Re(a_{\eta N}) \approx 0.20$ fm would probably permit bound states to occur only for nuclei with $A > 10$. However, the large width of the heavy eta-nuclear systems might render the bound states unobservable for too large a value of A.

It is imperative to accurately determine the magnitude of $a_{\eta N}$ by obtaining new, precise $\pi^- p \rightarrow \eta n$ data near the η -production threshold. This new eta production data with pions will extend the complementary experiments of eta photoproduction, $\gamma p \rightarrow \eta p$, in progress at Mainz and Bonn. Combining the electromagnetic interaction with the hadronic interaction, one can perform a coupled-channel analysis of the (π, π), (π, η), and (η, η) reactions together with the photoproduction processes (γ, π), and (γ, η). Since high-quality (π, π) data are currently available and new (γ, π) are soon to be available from CEBAF, the (π, η) process remains as the only gap that needs to be closed. Such a coupled-channel analysis will not only allow the precise determination of resonance parameters such as $S_{11} \rightarrow N\pi$, $S_{11} \rightarrow N\eta$, and $S_{11} \rightarrow N\gamma$, but will also provide access to the ηNN-vertex.

In contrast to the πNN-vertex, little is known about the ηNN vertex. In the case of pion scattering and pion photoproduction, the πNN coupling is preferred to be pseudovector (PV), in accord with current algebra results and chiral symmetry. However, because the eta mass is so much larger than the pion mass - leading to large SU(3) x SU(3) symmetry breaking - and because of the $\eta - \eta'$ mixing, there is no compelling reason to select the PV rather than the pseudoscalar (PS) form for the ηNN vertex.

The uncertainty regarding the structure of the ηNN vertex includes the magnitude of the coupling constant. This coupling constant, $g_{\eta NN}/4\pi$, varies between 0 and 7. The large couplings result from using fits of one boson exchange potentials, even though including the η yields only small improvements in fitting the NN phase shifts. From SU(3) flavor symmetry, all coupling constants between the meson octet and the baryon octet are determined by one free parameter α, giving

$$\frac{g^2_{\eta NN}}{4\pi} = \frac{1}{3}(3 - 4\alpha)^2 \frac{g^2_{\pi NN}}{4\pi}.$$

resulting in values for the coupling constant between 0.8 and 1.9 for commonly used values of α between 0.6 – 0.65, depending on the F and D strengths chosen as the two types of SU(3) octet meson-baryon couplings. A very recent study by Tiator, Bennhold and Kamalov [21] of new $\gamma p \rightarrow \eta p$ data from Mainz and Bonn finds clear evidence for a very small coupling constant of ≈ 0.4 along with a PS ηNN vertex. These values could be significantly improved by new, high-quality $\pi^- p \rightarrow \eta n$ data. From the above discussion, it appears that the ηNN coupling constant is much smaller compared to the corresponding πNN value of approximately 14, making the large η production cross section near threshold even more remarkable.

In contrast to pions which simultaneously excite $\Delta \left(I = \frac{3}{2}\right)$ and $N^* \left(I = \frac{1}{2}\right)$ states, the η meson, owing to its isoscalar nature ($I = 0$), can be used to selectively probe ($I = \frac{1}{2}$) N* states. A similar behavior is observed in K^-p interactions where I = 0 and 1 states are created. The $K^- p \rightarrow \Sigma\, \pi$ process probes both Λ^* and Σ^* resonances while the $K^- p \rightarrow \Lambda\, \pi$ reaction produces a pure I = 1 state that can only access $\Sigma^{*\prime}s$. Only through the $K^- p \rightarrow \Lambda\, \eta$ process is it possible to select the (I=0) Λ^* states.

Very little information exists on η hyperon systems. In the data for $K^-\, p \rightarrow \Lambda\, \eta$, a peak in the cross section appears near the $\Lambda^*(1670)$ resonance [22], but there are only a few data points, all with uncertainties of the order of 25% [fig. 3]. These data do not define the position of the peak and are not of sufficient quality to make an analysis of the shape and rise of the peak. A more detailed study of this region needs to be conducted. There is slightly more data from several experiments for the pure I = 1 reaction, $K^- p \rightarrow \Sigma\, \eta$ [23]. Once again, the cross section peaks near a resonance, the $\Sigma^*(1750)$. Table 1 illustrates that both of these resonances, the $\Lambda^*(1670)$ and $\Sigma^*(1750)$, are S-wave systems like the $S_{11}(1535)$ resonance and that all three have a large decay fraction to the η channel, despite a large handicap in phase space. This behavior clearly suggests that the baryon resonance $\rightarrow$ baryon + eta decay close to threshold should be described with the same underlying physics.

Just as the $\pi^- p \rightarrow \eta\, n$ process allows us to explore the ηN interaction, the $K^- p \rightarrow \Lambda\, \eta$ reaction opens the possibility to study the $\eta\Lambda$ interaction. These findings would be relevant for the field of hypernuclear physics, especially the area of double-Λ hypernuclei which are going to be studied in BNL experiment E885. The Λ - Λ interaction cannot have a long-range tail like the NN interaction since one-pion exchange is forbidden by isospin selection rules. Thus, in a construction of a One-Boson-Exchange potential, the η is the lightest meson that can contribute (pions can

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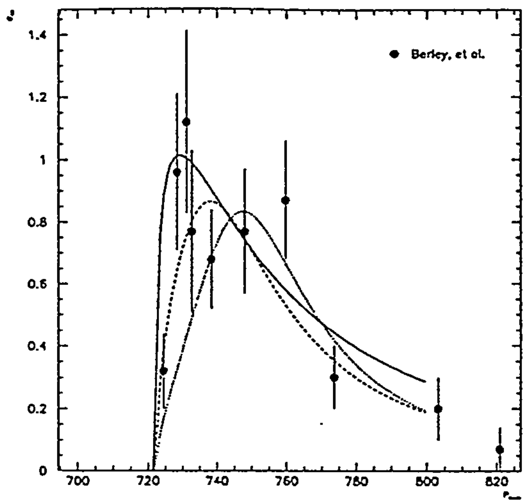


Figure 3: Comparison of the existing data for $K^- p \rightarrow \Lambda\ \eta$[22] with three different Breit-Wigner resonances of mass 1664 MeV/c^2 (solid), 1669 MeV/c^2 (dashed), and 1674 MeV/c^2 (dotted). The present quality of the data is insufficient to determine the peak.

only contribute through higher order box diagrams that involve intermediate Σ's). The current experimental information is sketchy at best, but seems to indicate that the Λ - Λ force is more attractive than the Λ - N interaction. Obtaining information on the Λ - Λ - η vertex via the $K^- p \rightarrow \Lambda\ \eta$ reaction will further our understanding of the Λ - Λ force in particular, and of the baryon-baryon interaction in general.

3 Experimental Method

We intend to identify η production using the same technique developed for AGS Experiment 890 (E890), namely by detecting the 2γ decay mode of the η. The kinematics for η production from $\pi^- p$ and $K^- p$ are essentially the same over our range of beam momenta, 720–760 MeV/c. We can then simultaneously measure both production reactions by identifying the kaons in the beam with a plastic Čerenkov counter. This tagging must be done in any case, since the π/K ratio in the C-8 line at these momenta is of the order of 5–7.

This experiment will be performed at the LESBII C-8 beam line using the same setup as for Experiment 890 which is scheduled to run this winter. Figure 4 depicts the experimental configuration for this experiment. The only modifications to this setup involve changes to the beamline necessary to use a kaon beam instead of a pion beam. This means changing the beam aperture at the mass slit opening and installing a plastic Čerenkov counter just upstream of the target chamber.

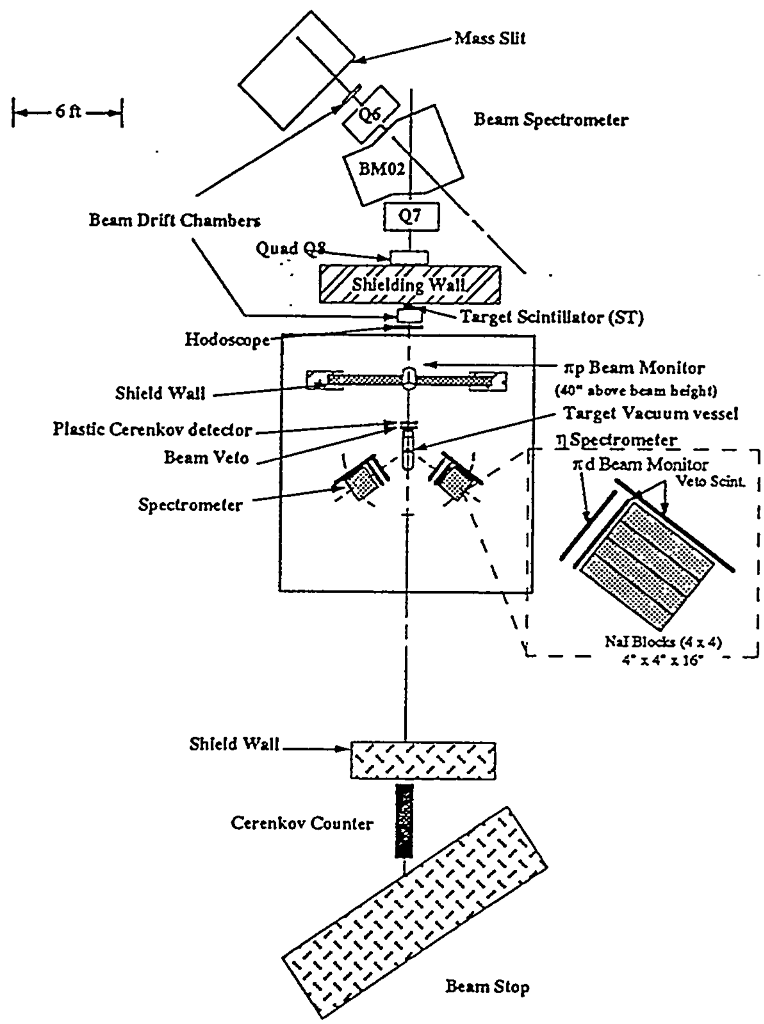


Figure 4: Experimental setup for E890 including changes necessary for using a kaon beam.

The pion beam monitoring consists of a magnetic spectrometer to measure the individual vector momenta and several monitors to measure flux as well as beam contamination from electrons. The magnetic spectrometer consists of the second beamline bending magnet, D2, and a series of wire chambers before and after this magnet. Scintillation counters out of the beam monitor the incident beam flux by detecting πp elastic scattering. The electron component of the beam is monitored with a gas Čerenkov counter. The muon component in the pion beam has been previously measured and found to be of the order of a few percent so it will not be monitored during this experiment. A set of four beam veto counters are mounted at the entrance to the target vacuum vessel to restrict the active beam area for background suppression. The actual target beam flux is monitored using scintillation paddles in conjuction with the spectrometer.

The kaon beam monitoring will only require the addition of a plastic Čerenkov counter to tag the pion component. This monitoring technique has been used previously in the C-6 beam line and presents no difficulty to install in the C-8 line. The momentum dispersion is typically 2-3% and the momentum resolution is typically 0.3%. We expect the beam characteristics to be similar to that for the C-6 line which typically are: $\sigma_x = 5$ cm, $\sigma_y = 0.5$ cm, $\sigma_{\theta(x)} = 24$ mr, $\sigma_{\theta(y)} = 16$ mr at the target.

The target for this experiment will be the same cryogenic LH_2 target that will be used in E890. The target is placed at the primary focus of the last quadrupole. It is 6.35 cm in diameter and 5.0 cm thick corresponding to 0.35 g/cm^2 of hydrogen. The target assembly is expected to contribute about 7% background and empty target runs will be conducted to subtract this background source.

The two photons from the η decay will be detected using the NaI calorimeters which were built by J. C. Peng *et al.* for the LAMPF η - spectrometer. Figure 4 shows the present configuration used by E890 with the calorimeters oriented in the horizontal scattering plane. This same setup will be used in this experiment. Charged-particle identification is accomplished using three scintillation veto counters that cover the front face of each calorimeter. In front of the scintillators, one inch of polyethylene is used to absorb low-energy charged particles. These veto counters do not form a hardware veto, rather decisions with respect to vetoing events are made during analysis. The total energy counters are a 4 X 4 array of optically-isolated NaI detectors that are 16 radiation lengths thick. The trigger is defined to be a beam trigger in coincidence with the two arms of the spectrometer. The beam trigger is defined as the coincidence of two scintillators (**S1, ST**) located in the beam.

The η has an at-rest lifetime of 0.78 x 10^{-18} sec and a branching ratio to two photons of 38.9%. Because the η has a relatively large mass, the opening angle for the two decay photons is about 130° for both the $\pi^- p$ and $K^- p$ reactions. Therefore the calorimeters can be placed at large angles with respect to the beam which has the benefit of providing relatively low singles counting rates. It also means that the invariant mass determination is dominated by energy resolution, so good angular resolution is not required. The two photon invariant mass is used to identify η particles and is determined by measuring the energy and direction of the two photons from the decay of the η. Figure 5 shows recent results from the E890 summer run for $\pi^- p \rightarrow \eta n$ at an incident pion momentum of 720 MeV/c. The resolution for the η invariant mass was 32 MeV/c, which allowed a clean separation of the η peak from background. The only significant background in this spectrum came from η production in the target vessel and thermal insulation surrounding the target.

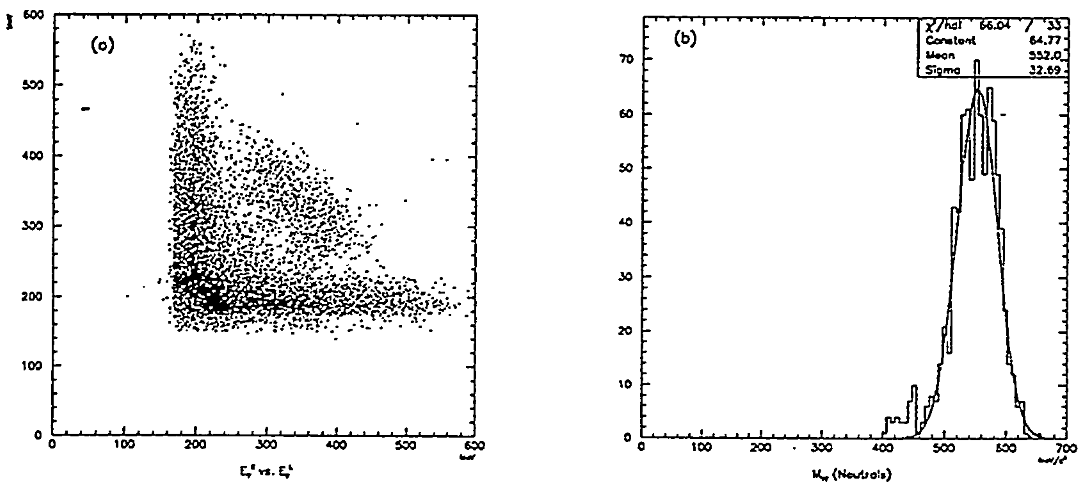


Figure 5: (a) Energy deposited in the left calorimeter versus energy deposited in the right calorimeter. Note the clean separation of background from the η locus. This background is eliminated by applying an energy cut on each arm of 0.24 GeV. (b) Invariant mass spectrum for neutral events which pass the energy threshold cut.

The actual beam flux on the target is measured using three scintillation counters on each spectrometer arm. The counters are located in front of the veto scintillators. Charged particles are identified using dE/dx from these counters and the veto counters along with energy measurements from the NaI. These monitors will detect elastic $K^- p$ scattering at the symmetric angle of 48° in the lab.

Knowledge of our acceptance is an important aspect of these measurements. We will determine our acceptance by Monte Carlo and calibrate this calculation by comparing a measurement of the $\pi^- p \rightarrow \eta\, n$ cross section with and without a collimator in front of one of the spectrometer arms. This technique has already been used successfully in a precision measurement of the branching ratio for $\eta \rightarrow \gamma\gamma$ [24].

3.1 Background

We have studied various systematic and background effects such as vetoing events due to the charged decay mode $\Lambda \rightarrow \pi^- p$ and misidentified events due to the detection of a photon from the neutral decay $\Lambda \rightarrow \pi^\circ n$ for both η production and $2\pi^\circ$ production. Monte Carlo studies indicate the charged-decay background to be of the order of 6%, the detection of a photon from the neutral π^0 decay to be 18%, and the $2\pi^\circ$decay mode to be negligible. The events vetoed by the charged-decay mode can be recovered based on our study of the recovery of vetoed events from the reaction $\pi^+ d \rightarrow \eta pp$. Figure 6 shows the invariant mass spectrum for the neutral decay background which includes our experimental resolution. The spectrum has not been normalized to the expected production rate. About 36% of these events result in an invariant mass outside the normal η invariant mass range (0.45 – 0.6 GeV/c) and these events all fall above an invariant mass of 0.6 GeV/c where there is presently no background. These events, then, can be identified and provide no significant problem.

3.2 Resolution

To determine the necessary statistical accuracy needed for this measurement, we have used Monte Carlo to study the response of our apparatus to η production from $K^- p \rightarrow \Lambda\ \eta$ for different values of the resonant mass for the $S_{01}(1670)$. The existing data for this reaction were parameterized using a Breit-Wigner formula. The resonant mass was then varied by ± 5 MeV. Figure 3 shows the existing data along with our evaluation for the three resonant mass values. The high and low mass curves were convoluted with the experimental beam distribution, and then used as the energy dependent cross sections for η production to generate events for our Monte Carlo. The results of this analysis which include our experimental resolutions are shown in figure 7. The data are binned in steps of 3 MeV/c. Statistical errors are $\sim$4% and about the size of the markers. Clearly, a difference of a few MeV in the resonance mass can be distinguished with data between 720 – 760 MeV/c beam momenta even with 10% statistics.

We have also estimated our angular resolution for the η CM scattering angle to

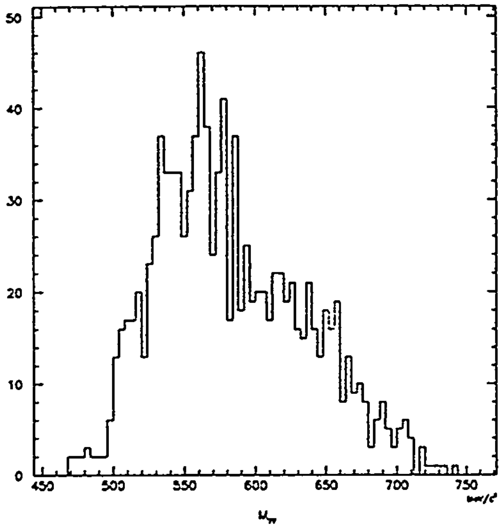


Figure 6: Invariant mass spectrum for $K^-p \rightarrow \Lambda(n\pi^\circ)\eta$ in which at least one photon from the π^0 of the Λ was detected in the calorimeters. Constraints included an energy threshold requirement for each arm of 0.24 GeV.

be about 16°. Figure 8 shows the angular distribution we expect for two opening angles of the spectrometer for η production from K^-. Therefore, we can select angle bins of $\sim 30°$ for determining the angular distributions of η production, obtaining 6 angles using two different opening angles of the spectrometer. According to figure 8, dividing each distribution into 3 approximately equal areas would give mean angles of $5°, 30°, 52°, 70°, 105°, 125°$, and $150°$.

Obviously, we need to know our absolute beam momentum very well to measure the threshold η production. The beam spectrometer has been calibrated using the Moby Dick spectrometer on the C-6 beamline to about 1 MeV/c. However, we cannot calibrate the C-8 beamline in this fashion. We can rely on the C-6 calibration; or we can check it by measuring the TOF difference between forward and backward scattered neutrons from the $\pi^-p \rightarrow n\,\eta$ reaction with our neutron counters. Data from this summer have demonstrated that we can calibrate the beam momentum relative to the η threshold to ≤ 3 MeV/c. This should be sufficient for these measurements.

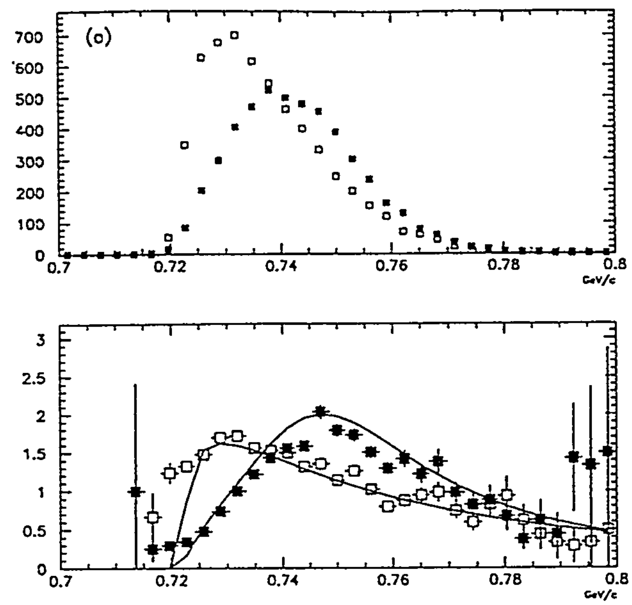


Figure 7: Simulation of our experimental response to η production from $K^-p \rightarrow \Lambda\ \eta$ for two different mass values for the $S_{01}(1670)$ resonance, 1674 MeV/c (solid squares) and 1664 MeV/c (open squares). The data are summed over 3 MeV/c bins and a beam momentum of 740 MeV/c with $\Delta P/P = 3\%$ has been used to generate the events. (a) Raw yield as a function of beam momentum without acceptance correction, and (b) Estimate of the cross section in arbitrary units after experimental acceptance has been taken into account.

4 Schedule

AGS E890 is scheduled for ~950 hours of beam time from the start of the winter run of the AGS. This run is expected to begin after 1 January 1995. We would like to start our run at the conclusion of the E890 running time. The total time requested is 600 hours. We have used the following quantities for our rate estimates: an expected beam flux of $2 \times 10^4 K^-/Tp/spill$, an acceptance of 0.23%, and a target thickness of 0.35 g/cm^2 which results in a detection of 9.5 $\eta' s$/(Tp-mb-hour). Assuming a nominal proton flux of 3 Tp and an average cross section of 0.3 mb for the $K^-p \rightarrow \Lambda\eta$ reaction, this equates to an event rate of 8.6 /hour. Four hundred hours are needed to obtain ~7% statistics at the peak of the distribution for 6 angles at a beam momentum of 740 MeV/c. Based on the rates seen in E890, we will need approximately 100 hours

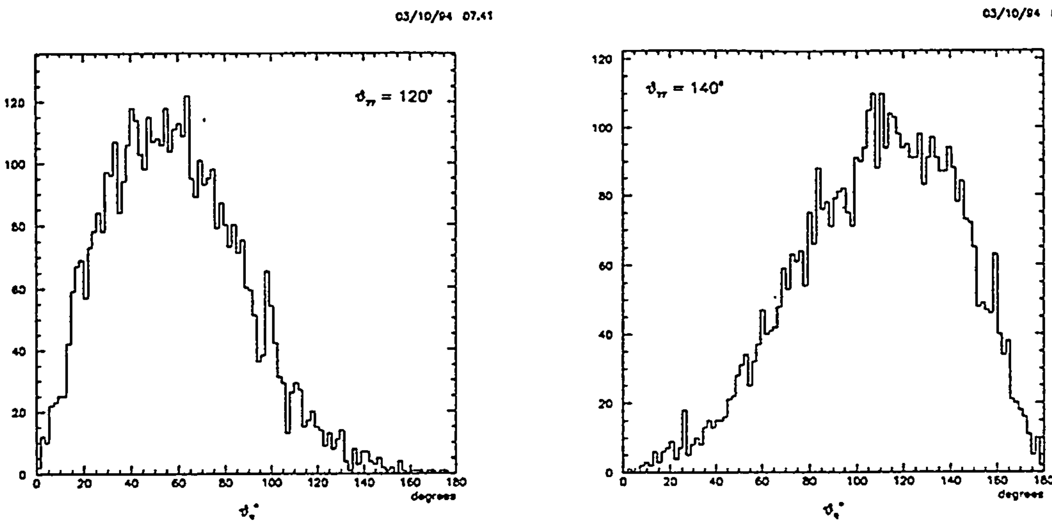


Figure 8: Monte Carlo angular distribution of the η CM scattering angle for a spectrometer opening angle of 120° and 140°.

of running time to study the angular distribution of the cross section for $\pi^- p \rightarrow \eta\, n$ at 690 and 720 MeV/c. We will take 740 MeV/c data concurrently with $K^- p$. These data should be taken immediately after the completion of E890 since no changes in the setup are required. In addition, we will need about 100 hours for setup and tuning of the kaon beam in the C-8 beamline.

References

[1] M.E. Sadler *et.al.*, Invited paper, 3rd International Symposium on Pion-Nucleon and Nucleon Physics, Leningrad (1989).

[2] R. A. Arndt *et al.*, Phys. Rev. D43, 2131(1991).

[3] B.M.K. Nefkens, invited paper presented at the Workshop of Future Directions in Particle and Nuclear Physics at Multi-GeV Hadron Facilities, BNL March 1993.

[4] M. Clajus and B.M.K. Nefkens, πN Newsletter, 7, 76 (1992).

[5] G. Höhler, Proceedings of the 5^{th} International Symposium on Meson-Nucleon Physics and the Structure of the Nucleon, Vol. II, G. Höhler, W. Kluge, B.M.K. Nefkens, Editors, πN Newsletter, 9, 1 (1993).

[6] L. Tiator, C. Bennhold, S.S. Kamalov, Proc. of the Inter. Conf. on Mesons and Nuclei at Intermediate Energies, Dubna, Russia, May 3-7, 1994, World Scientific, in press.

[7] B.M.K. Nefkens, Proc. of the Inter. Conf. on Mesons and Nuclei at Intermediate Energies, Dubna, Russia, May 3-7, 1994, World Scientific, in press and references contained within.

[8] E. Chiavassa *et. al.*,Proc. of the Inter. Conf. on Mesons and Nuclei at Intermediate Energies, Dubna, Russia, May 3-7, 1994, World Scientific, in press.

[9] J. Berger *et. al.*, Phys. Rev. Lett. **61**, 919 (1988); F. Plouin *et. al.*, Phys. Rev. Lett. **65**,690 (1990).

[10] R. Kessler *et. al.*,Phys. Rev. Lett. **70**, 892 (1993) and Phys. Rev. **D50**, 92 (1994).

[11] R. Frascaria *et. al.*, Phys. Rev. **C50**, R537 (1994).

[12] C. Wilkin, Phys. Rev. **C47**, R938 (1993).

[13] W.J. Briscoe *et al.*, LNS Proposal 288 (1993).

[14] D. M. Binnie it et al., Phys. Rev. **D8**, 2783 (1973).

[15] R. M. Brown *et. al.*, Nucl. Phys. **B153**, 89 (1979).

[16] F. Bulos *et. al.*, Phys. Rev. **187**, 1827 (1969).

[17] W. Deinet *et. al.*, Nucl. Phys. **B11**, 495 (1969).

[18] W. B. Richards *et. al.*, Phys. Rev. **D1**, 10 (1970).

[19] M. Arima *et. al.*, Nucl. Phys. **A543**, 613 (1992).

[20] R.S. Bhalerao and L.C. Liu, Phys. Rev. Lett. **54**, 865 (1985).

[21] L. Tiator, C. Bennhold, and Kamalov, Nucl. Phys. **A** (1994) in press.

[22] D. Berley, *et. al.*, Phys. Rev. Lett. **15**,641 (1965).

[23] M. O. Jones, *et. al.*, Nucl. Phys. **B73**, 141 (1974).

[24] D. White *et al.*, Proceedings of the Annual Meeting of the APS Division of Particles and Fields, Albuquerque, August 1994.

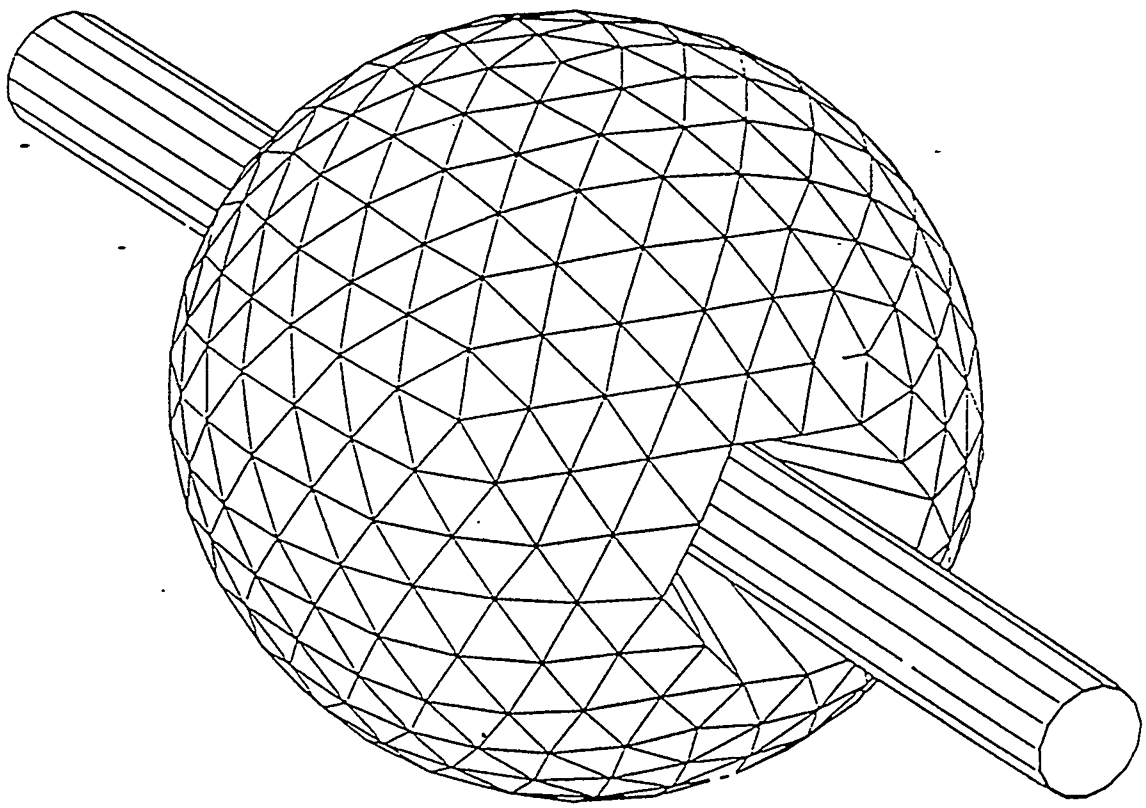
D. Future Experiments Using the Crystal Ball

The impressive Crystal Ball detector at SLAC is ideally suited for measuring decays of the η meson and for measuring all-neutral final states. It has been used extensively at SPEAR and DORIS but is presently being stored at SLAC. The detector was originally requested for BNL Proposal #897, *Tests of C and CP in Rare Eta Decays with the Crystal Ball Detector*, B. M. K. Nefkens and R. E. Chrien, Spokespersons. The proposal was turned down because of the lack of funds to transport the detector to BNL and to upgrade the electronics and data acquisition, the expressed desire of the PAC to see a broader physics application for the Crystal Ball before approving this cost, and the feeling that the program needed more collaborators for a project of this size. Another proposal, *Baryon Spectroscopy with the Crystal Ball*, M. E. Sadler and W. B. Tippens, spokespersons, will be submitted for consideration to the April PAC. This proposal will be to use the Crystal Ball to measure differential cross sections for $\pi^- p \to \pi^o n$, $\pi^- p \to \gamma n$, $\pi^- p \to \eta n$ and $\pi^- p \to \pi^o \pi^o n$ in the momentum region 0.4 - 1.9 GeV/c. A letter of intent is also being prepared to measure the angular distributions of K^- interactions leading to Λ or Σ° plus γ, π°, η, or $\pi^\circ\pi^\circ$ final states.

The SLAC Crystal Ball is a highly segmented, total energy, electromagnetic calorimeter and spectrometer, covering over 94% of 4π steradians. It consists of 2 major detectors: the ball proper and the charged particle tracker, which is located on the inside of the ball. The ball, shown in Fig. 1, is constructed of 672 optically isolated NaI(Tl) crystals, 15.7 radiation lengths thick. Each crystal is viewed by its own photomultiplier. The counters are arranged in a spherical shell with an inner radius of 25.3 cm and an outer radius of 66 cm. The shell has an entrance and exit tunnel for the beam, target plumbing, and tracker cables. Electromagnetic showers in the ball are measured with an energy resolution of $\sigma/E = 2.7\%/[E(GeV)]^{1/4}$. Shower directions are measured with a resolution in θ, the polar angle with respect to the beam axis, of $\sigma = 2° - 3°$ for energies in the range 50-500 MeV; the resolution in ϕ is $2°/\sin\theta$.

With the Crystal Ball, complete angular distributions for $\pi^- p \to \pi^o n$, $\pi^- p \to \gamma n$, $\pi^- p \to \eta n$ and $\pi^- p \to \pi^o \pi^o n$ can be measured simultaneously and only one beam normalization per momentum will be needed. This experiment is a natural extension to higher momentum of the completed LAMPF πN program. The investigators have been active for some time in evaluating the physics objectives extending this program to higher energy. Sadler, with W. R. Gibbs (formerly at T division at LANL, presently at New Mexico State) co-authored the section "Baryon Resonances at PILAC" for the final report, *User's Group Report on Physics with PILAC*, October 15, 1991.

Crystal Ball
Multi-photon Spectrometer



672 separate NaI(Tl) crystals
94% solid angle; with endcaps~98%
$\sigma / E = 0.027 / \sqrt[4]{E}$ (E in GeV)
$\phi_{ext} = 1.32$ m $\phi_{cavity} = 0.50$ m $\sigma_{\theta} \approx 2^{\circ}$-$3^{\circ}$ $\sigma_{\phi} = 2/\sin\theta$ $t = 16\ \chi_0$

Figure 1. The Crystal Ball

1. Motivation for a Renewed Effort in Baryon Spectroscopy

Although neither the PILAC (Pion Linear Accelerator) facility at Los Alamos nor the KAON facility at TRIUMF are apparently going to be built, the physics needs remain the same: a hadron facility with pion beams up to 2 GeV is needed to make comprehensive measurements (differential cross sections and polarization observables) in the second and third resonance regions. The measurements would be similar to the πN program just completed at Los Alamos (described in previous progress reports), except at higher energy. Such measurements are needed to complement the experimental program at CEBAF, providing more accurate information on the πNN^* vertex.

Understanding the strong interaction is a major goal of nuclear and particle physics. The study of the structure of baryons in terms of the underlying quark and gluon degrees of freedom of QCD, now the best candidate for the theory of strong interactions, provides valuable tests for this theory.

An extensive new program of experimental study of baryon resonances, excited states of nucleons, is needed in order to realize these goals. It was the rich spectrum of baryon resonances and mesons that led to the development of quark models of hadrons. Some of these models have been quite successful in describing the spectrum (and many properties of the hadrons) in terms of constituent quarks. The relation of these models to QCD, however, has not been established.

Previous experimental and theoretical research results suggest some specific experimental goals that could lead to remarkable developments in the study of how QCD is realized in nature. One crucial aspect of excited nucleon states is the role of gluonic degrees of freedom. At present there is no compelling experimental evidence that gluonic modes must be included in order to account for the excitation of any baryon resonance; yet there are compelling theoretical arguments that the excitation of gluonic modes should occur. Because of the difficulty in developing models based directly on QCD in the soft region, guidance from improved experiments is necessary.

There have also been phenomenological models of hybrid baryon resonances that are valuable in providing some guidance for experiments. Proposed experiments on baryon resonance electroproduction that seem most promising for providing evidence of gluonic degrees of freedom are motivated in part by such models. All of the known baryon resonances have been discovered via hadronic probes; however, a new era for the study of baryon resonances is beginning in the 1990's with the development of high-duty-factor electron accelerators. In particular, CEBAF will have sufficient energy to produce all of the N and Δ resonances in the Particle Properties Summary Table. In order to make full use of the results of the CEBAF baryon resonance electroexcitation experiments, it is essential that improved pion excitation experimental data be available. It is expected that the CEBAF baryon spectroscopy program (the N* Collaboration) will start in 1996, so there is some urgency in developing the complementary πN program.

In the second resonance region there are a number of specific problems for which pion experiments are very important. New experimental studies[3] of the P_{11}(1440) [the Roper resonance] and the S_{11}(1535) are motivated by specific questions related to QCD. Other important questions which motivate new experiments in this region of 1.4 -1.6-GeV resonances are discussed in the following paragraphs.

Experimental studies of the P_{11}(1440) resonance are strongly motivated by the observation that the lowest hybrid baryon (a qqqg configuration) in bag models[1] is expected to be a P_{11} resonance. There has been a great deal of controversy about the analysis of this broad resonance. If the conventional picture of the Roper resonance as a radial excitation of the nucleon is correct, this resonance is mainly excited by longitudinal transition amplitudes. In the hybrid model[1] however, the longitudinal γNN* transition amplitude is greatly suppressed.[2] In the analysis of CEBAF experiments to extract the gamma transition amplitudes, the πNN* vertex must also be included, since these are pion electroproduction experiments. A detailed pion excitation experiment is necessary for a satisfactory analysis of the Roper. This provides an excellent opportunity for an important discovery in hadronic physics with critical implications for QCD-based models of hadrons.

The Roper amplitudes display an unusual Q^2 dependence that could be investigated with higher energy studies. The world's first complete data sets for πN scattering have been obtained at LAMPF by the UCLA-ACU-GWU collaboration in the region up to the Roper resonance. Higher energies are needed to complete this task.

The emphasis on the S_{11}(1535) resonance at CEBAF[3] is motivated by several results of previous studies. The most important observation is that the S_{11}(1535) resonance has a large branching ratio for decay into a nucleon and an eta. This feature is essential in the CEBAF study of this resonance. That study is motivated in part by the unusual Q^2 dependence of the amplitudes. Since the electroproduction amplitude of the S_{11}(1535) is obtained from an analysis of the η electroproduction amplitude, detailed information about π-η production amplitudes at the S_{11}(1535) resonance is essential for the success of the CEBAF project. This set of complementary experiments could then be used to examine the unusual momentum dependence to see if there is a characteristic QCD effect.

Another possible candidate for a hybrid baryon is the $P_{11}(1710)$ in the third resonance region. Arguments analogous to that given for the $P_{11}(1440)$ apply in this case. For this resonance, π-η production is also essential for the interpretation of the accepted CEBAF experiment on this resonance. Pion experiments give specific information on the ηNN^* vertex needed for the understanding of gluonic excitations.

The capability of studying 2π, η, and other final states with pion excitation of N*'s would make a pion program invaluable in the search for gluonic excitations and for the development of QCD-based models. In addition to detailed information about known resonances, this program could help complete the spectroscopy of baryon resonances. The answers to questions of states predicted in certain models and not seen in experiments and the detection of exotic states, states not predicted in constituent quark models, will provide important information for the development of QCD-based theories. Moreover, it is crucial to study N* excitations at high Q^2 in order to attempt to trace the evolution to the region of applicability of perturbative QCD[4].

A pion program at the Brookhaven AGS could cover the low-lying D_{13} and S_{11} resonances and the cluster of resonances in the mass range of 1.6 -1.7 GeV. Here, six established (3- or 4-star) isospin-1/2 resonances are degenerate when the uncertainties in their masses and widths are taken into account. Better π-p data (particularly $\pi^- p \rightarrow \pi^o n$) are sorely needed in this energy range in order to disentangle the structure of these states. The situation is further clouded because questionable charge exchange data[5] were heavily used by both the Karlsruhe-Helsinki and CMU-LBL partial-wave analyses (on which the resonance parameters are based). These data apparently need to be shifted by ~5% in momentum. Further, the backward-angle data for the analyzing powers lead to violations of isospin invariance by three standard deviations when combined with the accurate elastic data from PNPI and LAMPF. Our charge-exchange data from LAMPF are consistent with isospin invariance and do not agree with Brown, et al., at the back angles near P_π = 650-700 MeV/c, where the measurements overlap.

2. Survey of Existing Data in the Region $0.4 \leq P_\pi \leq 2.0$ GeV/c

Better data for pion-nucleon charge exchange, $\pi^- p \rightarrow \pi^o n$, are sorely needed in the resonance region. As an example, most of the world's data sets for this reaction have data near $\theta_{cm} = 150°$. Therefore, an excitation function of the these data is shown in Fig. 2, along with partial-wave analyses from the VPI, Karlsruhe-Helsinki and

CMU-LBL groups. Much of the data are of little consequence due to their large error bars. Of particular note are the small error bars for the data of Brown, et al.[5], and the fact that these data seem to determine the predictions for this observable for all of the PWA's. As already stated, these data are suspected to be off by ~5% in the calibration of their absolute momentum and have been shown to be in violation of isospin invariance. We showed, as part of our LAMPF program, that there was no violation of isospin invariance at the higher end of our momentum range (the lower end of Brown, et al., where the violation was the largest).

The data for the analyzing power, A_N, for $\pi^- p \rightarrow \pi^o n$ are in even worse shape, as shown in Fig. 3. The only comprehensive data are those from Brown, et al., but none of the PWA's are able to reproduce them. Thus, we are led to believe that the information on baryon spectroscopy from πN partial-wave analysis is sorely deficient due to poor quality (and probably erroneous) data for πN charge exchange.

Turning the attention now to the reaction $\pi^- p \rightarrow \gamma n$, a summary of existing data at 500 MeV for the inverse reaction, $\gamma n \rightarrow \pi^- p$, is shown in Fig. 4. Most of these data were obtained using deuterium as the 'neutron' target. Two techniques are used: 1) measuring π^-/π^+ ratios from deuterium coupled with cross section data for $\gamma p \rightarrow \pi^+ n$, and 2) measuring $\gamma d \rightarrow \pi^- pp$ and extrapolating to the kinematic region where one proton is a spectator. Both techniques are complicated by the effects of the Fermi motion of the neutron in deuterium and by nuclear shadowing, off-mass-shell effects and the Pauli principle. Interestingly, the only data in Fig. 4 that measure $\pi^- p \rightarrow \gamma n$ directly (Kim, et al. [6] from our UCLA-ACU-GWU collaboration at LAMPF) are 2-3 standard deviations below $\gamma n \rightarrow \pi^- p$ data. The data for $\pi^- p \rightarrow \gamma n$ (which correspond to $P_{\pi^-} = 471$ MeV/c) have been corrected by the detailed balance factor given by

$$\frac{d\sigma}{d\Omega}(\gamma n \rightarrow \pi^- p) = \frac{p_\pi^2}{2\, p_\gamma^2}\frac{d\sigma}{d\Omega}(\pi^- p \rightarrow \gamma n)$$

where p_π and p_γ are the cm momenta for the $\pi^- p$ and γn systems, respectively.

The primary reason so few data are available for the more direct $\pi^- p \rightarrow \gamma n$ reaction is the difficulty in separating out the contribution from hadronic reactions, primarily charge exchange, $\pi^- p \rightarrow \pi^o n$. The almost 4π geometry of the Crystal Ball provides the capability of discriminating against multiple γ rays that might arise from the decay of π°, η, or $\pi^\circ\pi^\circ$. The situation has been investigated with GEANT, taking into account all 672 NaI crystals with the advertised energy resolution. The resulting distribution in reconstructed scattering angle, θ_γ, as a function of the reconstructed total energy, $E\gamma$, is shown in Fig. 5a for 9700 events. The same distribution is shown for γ rays from $\pi^- p \rightarrow \pi^o n$, $\pi^\circ \rightarrow \gamma\gamma$, in Fig. 5b, but with only events in which one and only one γ ray is detected. The paucity of γ's in the middle of the kinematically allowed region in Fig. 5b is due to the presence of another γ being detected in a distinctly different region of the Crystal Ball. Some events leak through in the kinematic region that could be confused with γ's from $\pi^- p \rightarrow \gamma n$. A summary of a sample analysis is given in Table 1.

	$\pi^- p \rightarrow \gamma n$	$\pi^- p \rightarrow \pi^o n$, $\pi^\circ \rightarrow \gamma\gamma$
Sample size	9700	9700
1-γ events	7521	2070
Kinematic cut	5191	81 ($60^\circ \leq \theta_\gamma \leq 180^\circ$)
Kinematic cut	1663	14 ($80^\circ \leq \theta_\gamma \leq 100^\circ$)

Table 1. Results of the analysis of single-γ events in the Crystal Ball.

Thus, the large solid angle acceptance of the Crystal Ball produces a rejection factor of 60-120 for the 'background' from $\pi^- p \rightarrow \pi^o n$. After accounting for the fact that the total cross section ratio for $\sigma(\pi^- p \rightarrow \pi^o n)/\sigma(\pi^- p \rightarrow \gamma n) \sim 50$, one expects to have a signal to background of ~1-2 to 1 for the measurement of $\pi^- p \rightarrow \gamma n$. This ratio is much better than what was obtained in our LAMPF data which employed a n-γ coincidence, without the associated uncertainties in determining and monitoring the efficiencies of neutron counters.

Finally, another excitation function for the recoil proton polarization (P) for $\gamma n \rightarrow \pi^- p$ is shown near 90° as a function of energy in Fig. 6. This observable is the same as the analyzing power (A_N) for $\pi^- p \rightarrow \gamma n$ obtained with a polarized proton target. Again, the data from Kim, et al.[6], the recent TRIUMF data by Stasko, et al.[7], and the limited PSI data by Alder, et al.[8], were obtained from the analyzing powers for $\pi^- p \rightarrow \gamma n$. These data tend to have smaller error bars than the measurements of the proton polarization for $\gamma n \rightarrow \pi^- p$. The measurements of polarization observables using a polarized target with the Crystal Ball will be a very important subsequent phase of the program.

Summarizing, an ongoing resonance program with meson beams is needed to complement the CEBAF N* program. The Brookhaven AGS is the best existing accelerator to implement a program. Discussion here has concentrated on the utilization of pion beams, but the same arguments can be made for kaon beams.

References for Sec II:

1. T. Barnes and F. E. Close, Phys. Lett. **123B**, 89; **128B**, 277 (1983); E. Golowich, E. Haqq, and G. Karl, Phys. Rev. **D28**, 160 (1983).
2. Z. Li, V. Burkert, and Z. Li, CEBAF-PR-91-032 (1991).
3. S. Dytman and K. Giovanetti, spokesmen, *A Study of the $S_{11}(1535)$ and $P_{11}(1710)$ in $p(e,e'p)\eta$*, N* Collaboration at CEBAF.
4. P. Stoler, Phys. Rev. Lett. **66**, 1003 (1991).
5. R. M. Brown, et al., Nucl. Phys. **B117**, 12 (1976), and Nucl. Phys. **B144**, 287 (1978).
6. G. J. Kim, et al., Phys. Rev. **D40**, 244 (1989).
7. J. C. Stasko, et al., Phys. Rev. Lett. **72**, 973 (1994).
8. J. C. Alder, et al., Phys. Rev. **D27**, 1040 (1983).

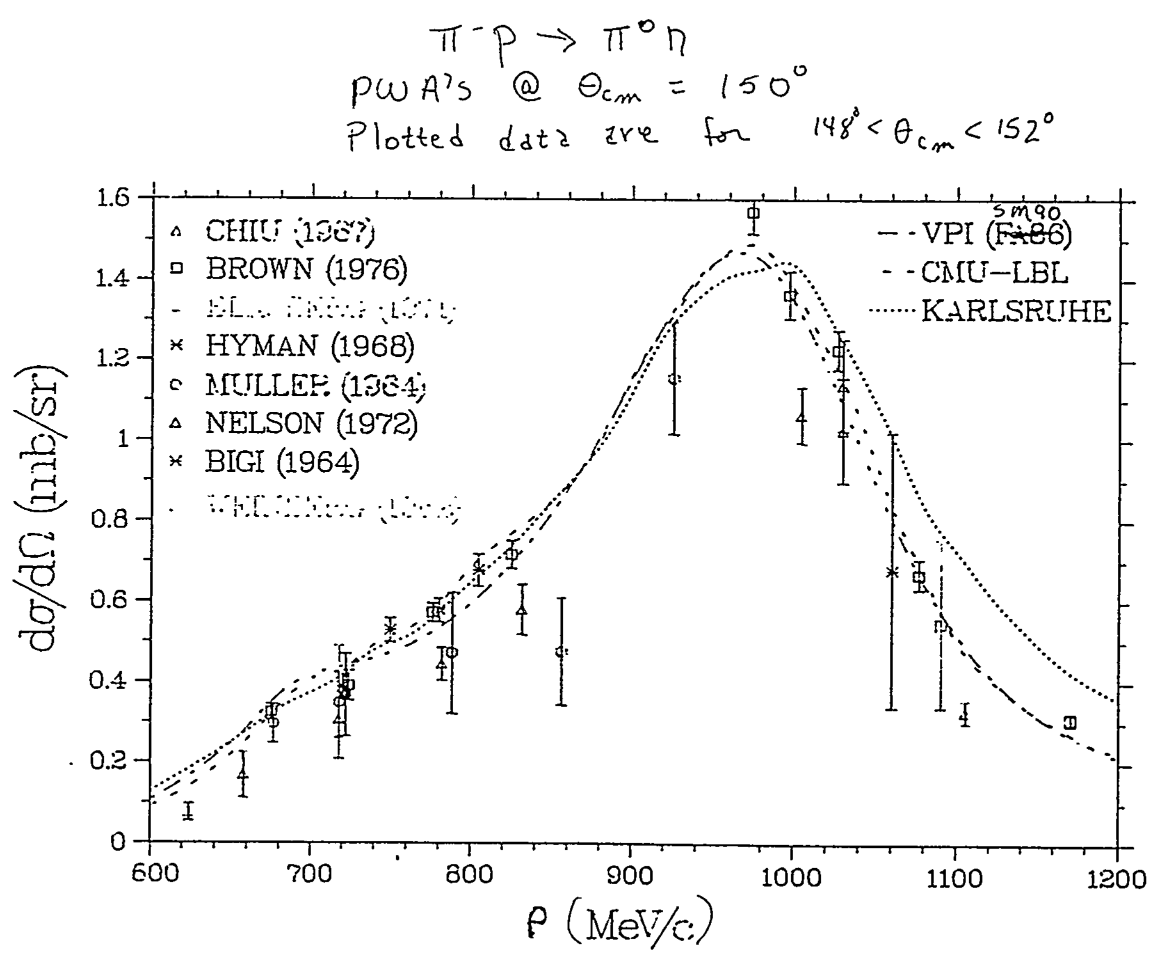


Figure 2. Survey of differential cross section data for $\pi^- p \rightarrow \pi^0 n$.

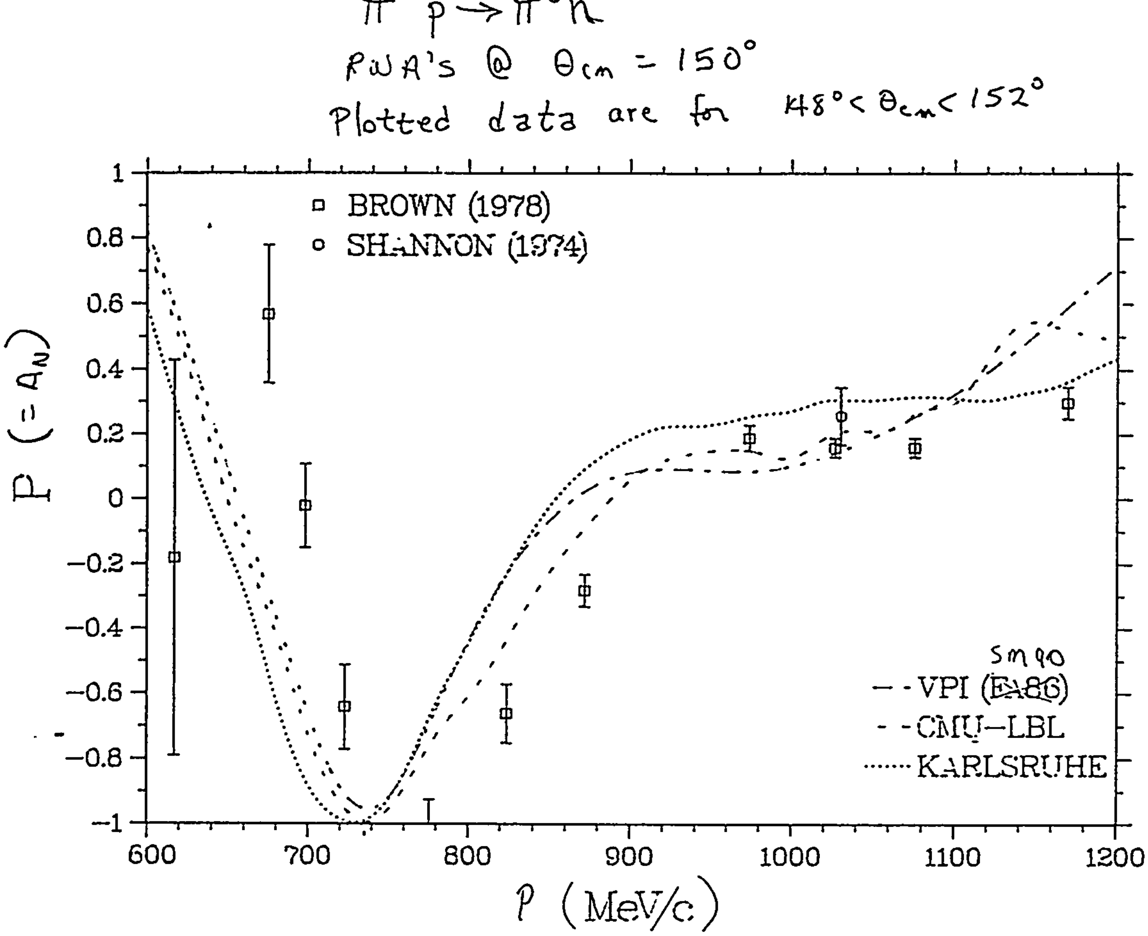


Figure 3. Survey of analyzing power data for $\pi^- p \rightarrow \pi^0 n$.

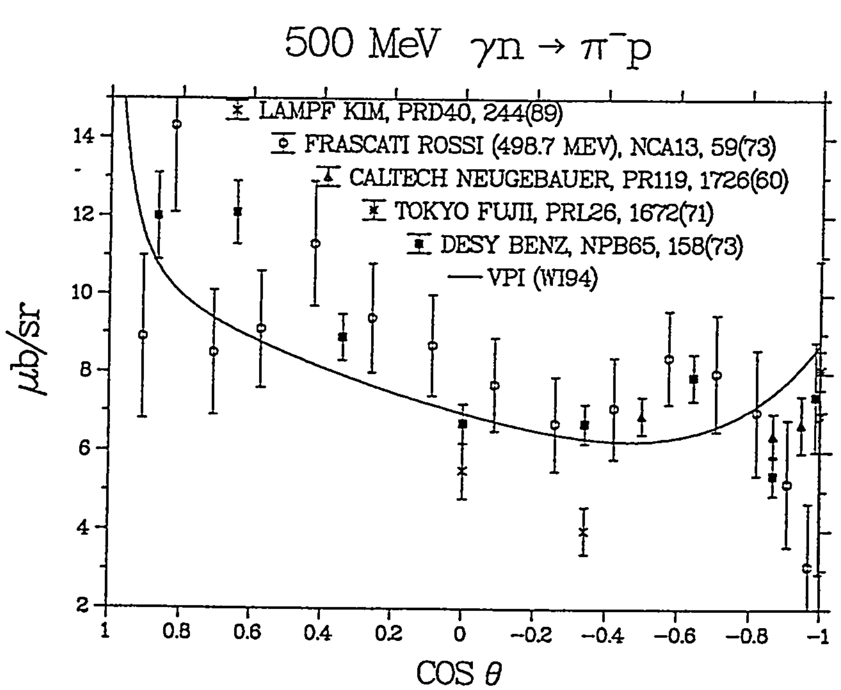


Figure 4. Sample experimental data for $\gamma n \rightarrow \pi^- p$.

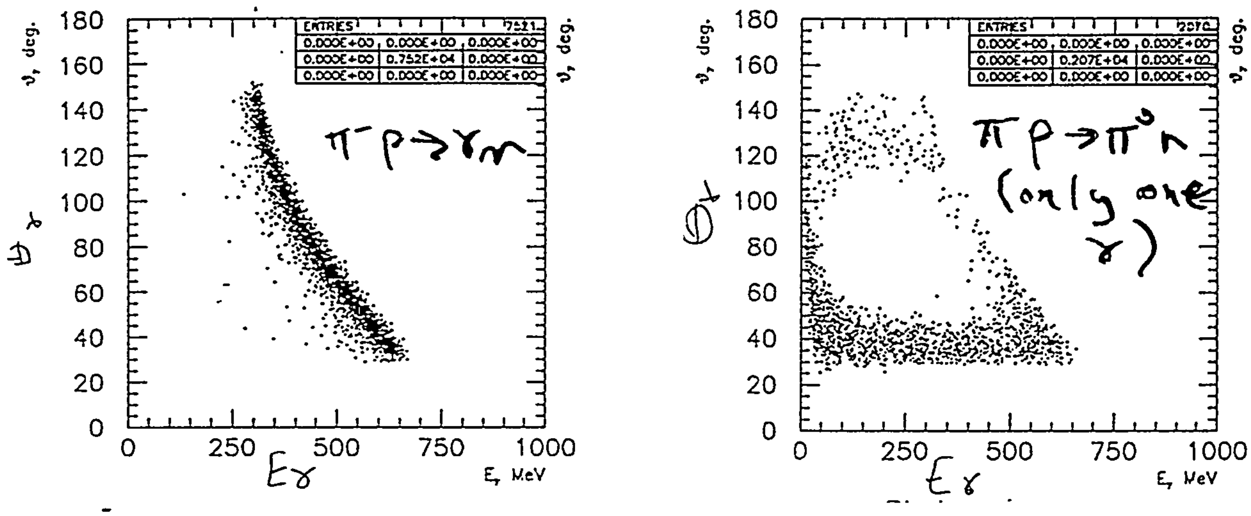


Figure 5. GEANT results showing how $\pi^-p \rightarrow \gamma n$ is separated from $\pi^-p \rightarrow \pi^o n$ using the Crystal Ball detector.

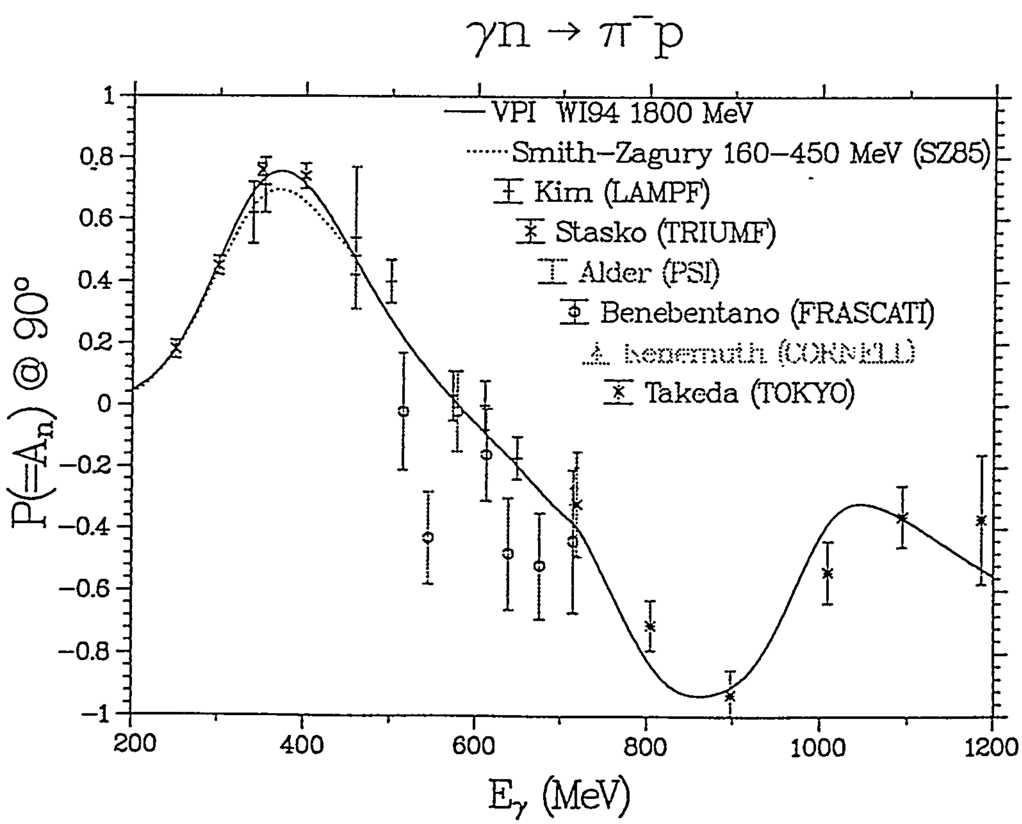


Figure 6. Survey of analyzing power data for $\gamma n \rightarrow \pi^-p$.

III. Fermilab Experimental Program

A. E789: Nuclear Dependence of Charm and Beauty Quark Production and a Study of Two-Prong Decays of Neutral D and B Mesons

1. Introduction

Abilene Christian University has been a collaborator since October, 1988 on Fermilab E789, a fixed target heavy-quark experiment. This collaboration consists of P25 (formerly P2) Division of the Los Alamos National Laboratory, Fermilab, Northern Illinois University, University of Chicago, University of California at Berkeley, University of South Carolina, Academia Sinica (Taiwan), and Abilene Christian University. The experiment used the E605/E772 spectrometer located at the Meson East experimental hall at FNAL.

This experiment was approved in October 1988 and began its test run in the summer of 1990. After the extended shutdown at Fermilab, data collection was resumed in August 1991 and was completed in January 1992. Due to new safety rules E789 was approximately one month later in its startup than other FNAL experiments and was not permitted to run at the proposed beam intensity resulting in a reduction in the amount of b-quark data; however, it has still been considered one of the successes of the last fixed-target run by FNAL management since it did obtain a good measurement of the b-quark cross section.

Roughly 1.5E9 events were written to ~1300 8mm tapes. The beam time was divided roughly equally between charm and beauty running conditions. Analysis of these data is now mostly complete but will still occupy the collaboration for the next 1-3 years as there are a number of results that may be obtained from the rich data set. Three papers were published in 1994 [8, 15,16] and a paper on the first measurement of the b-quark production cross section at 800 GeV has been submitted for publication. These results are discussed in Section A.3.

2. Physics goals

The goals of E789 are to measure rare two-prong decays of the neutral B and D mesons and to measure the nuclear dependence of charm (c) quark and beauty (b) quark production. The B meson study is motivated by the observation of a large amount of mixing in the meson system and that the amplitude for $b \rightarrow u$ conversion might be large [1] The D meson studies come essentially for free because the requirements for this work are a simplified version of that for the B mesons. The observation of charmless $B \to h^+h^-$ (dihadron) decays would contribute to the determination of the term in the Cabibbo-Kobayashi-Maskawa matrix, V_{ub}. Such two-prong decays have not yet been observed. One can find many papers on heavy quark physics and two papers of F. Gilman [2] have extensive reference sections that indicate the breadth of the interest in this field.

The nuclear dependence measurements are partially motivated by the success of FNAL E772, which used the same spectrometer and generated considerable interest in the nuclear physics community. E772 yielded the first high-precision A-dependence of Drell-Yan (DY) production [3]. In addition, it has produced the first measurements of the A-dependence of ψ' and Υ (upsilon) production.

E789 analysis will search for several expected b-quark states such as B_d, B_s, and Λ_b. Simultaneously with the proposed search for B_d, B_s, $\Lambda_b \to h^+h^-$ (e.g, $\pi^+\pi^-$, K^+K^-, $p\bar{p}$, $\pi^{\pm}K^{\mp}$ for meson decay, $p\pi^-$, $\bar{p}\pi^+$, pK^-, $\bar{p}K^+$ for baryon decay), the experiment will be sensitive to other b-quark decays. Sensitivity will exist for $B_d, B_s \to \mu\mu$, $e\mu$, ee; $B \to J/\psi$, ψ', χ_o; and $\eta_b, \Upsilon, \chi_b \to h^+h^-$. Information will be obtained on the mass, lifetime, and production dynamics of any state detected.

A list of some of the specific physics goals of this ambitious experiment are the following:

1) to extend the range in Feynman-x over which the nuclear dependence of J/ψ and ψ' production cross sections have been measured,
2) to study A-dependence of open charm production (J/ψ and ψ' data measure hidden charm, D meson data will measure open charm),
3) to study $D \to \pi K$ decays,
4) to study dileptonic D decay modes at the 10^{-7} branching ratio levels,
5) to produce the η_c and χ_c resonances of the charmonium system,
6) to determine the values (or upper limits) of the branching ratios for a variety of b-particle dihadronic decays and thus help determine V_{ub} of the CKM matrix,
7) to search for B_s and Λ_b,
8) to measure the lifetimes and masses of B_d, B_s, and Λ_b,
9) to measure the $B \to J/\psi X$, $\chi^0 X$, and $\psi' X$ inclusive decays,
10) to search for exclusive dilepton decays $B \to \mu^+\mu^-$, e^+e^-, μ^+e^-, μ^-e^+,
11) to study inclusive dilepton decays of $b\bar{b}$ pairs, and
12) to search for the η_b and for dihadron decays of Υ and χ_b states.

The expansion of the physics goals of E789, which initially was to search for charmless beauty decays, was prompted, in part, by the increased interest in heavy quark production in relativistic heavy-ion collisions from CERN NA38, and by new results from Fermilab E772 on the A-dependence of J/ψ , ψ', and Υ production. Many theoretical models now attempt to describe the heavy-ion data as well as data from hadron-nucleus collisions (including older data from CERN NA3 and Fermilab E537) in a unified way. Taken together, the new experimental results and the theoretical interest which they have inspired, strongly suggest additional nuclear dependence measurements relating to heavy quark production and propagation.

The spectrometer used was the old E605 spectrometer [4] shown in Fig. 1, which is well known for its high resolution $\mu^+\mu^-$ studies of the Υ (upsilon) region. This same spectrometer was used in E772 to measure the nuclear dependence of J/ψ and ψ' production. This spectrometer is roughly 60 meters in length. There are two analyzing magnets, SM12 and SM3 which define the optics of the spectrometer. There is an internal beam dump inside SM12 which is the larger magnet immediately downstream of the target region. Between SM12 and SM3 is a set of drift chambers (Station 1) and an x-y hodoscope array (X1 and Y1; coordinate system is +**z** in beam direction, +**x** is beam left and +**y** is up in the lab). Following SM3 is a hodoscope array (Y2) and another set of drift chambers (Station 2). Next is the Ring Imaging Cherenkov (RICH) detector which consists of a 15 meter gas radiator volume with an array of mirrors at the end to reflect and focus the vacuum ultraviolet (VUV) Cherenkov light on two multistep avalanche chambers located on each side of the RICH. Following the RICH is a third set of drift chambers (Station 3), a third hodoscope array (X3 and Y3), an electron calorimeter, a hadron calorimeter, a fourth hodoscope array (X4 and Y4), a thick absorber, and a set of prompt tubes for the detection of muons.

The modifications to the E605/E772 setup included a new set of high rate drift chambers for Station 1, a microstrip vertex detector, changes in the aperture of SM12 to allow running at the low field values required for E789, and the modification of the hodoscope arrays at Stations 1, 2, and 3 (the latter project was carried out by ACU).

The silicon strip vertex detector (SSD) was the most important part of the spectrometer for the charm and beauty data (see Figure 2). It consisted of 16 planes of silicon strip detectors arranged into two arms, with 8 chips above and 8 chips below the horizontal plane. The strips were on a 50 μm pitch with 1024 strips/detector. About 10,000 channels were instrumented with readout electronics that had single RF time bucket (19 ns) resolution. A vertex processor was designed to provide a third level trigger for events containing a downstream decay vertex. Since B^o mesons in this energy range have an average decay length of about 1.2 cm, this detector is very valuable for triggering on beauty events. Likewise, a D° meson will travel about 0.4 cm before decaying, so it too can be separated from events originating from the target itself.

Another useful part of this spectrometer was the RICH detector. This was one of the first large RICH detectors built and has been described in several articles[6]. Combining its information with that of the electron and hadron calorimeters and the muon detectors, one obtains good $\pi/K/p/e/\mu$ separation. This is essential for the study of several of the decay channels discussed above. The RICH detector itself was not been modified, but the ADC's of the readout chain were replaced with LeCroy 1885 FASTBUS ADC's. ACU took a significant role in the commissioning of the new data acquisition electronics and in getting this detector back on line (it had not been used for several years).

Hadronic production of heavy quarks (c and b) from nuclear targets holds much interest for nuclear physics. At high energies ($\geq$100 GeV) the dominant production diagram is gluon fusion, $gg \rightarrow q\bar{q}$. Hence nuclear effects on the gluon structure function may be observable in measurements of the A dependence of charm and beauty production. The quarkonium resonances, J/ψ and Υ, have easily detectable experimental signals and can be used to analyze the dynamics of reaction processes.

3. Results

During the past year three papers have been published [8, 15, 16] and a fourth has been submitted for publication. Reference [8] was the measurement of charm production at large x_F. These results completely excluded the possibility of an intrinsic charm component in the proton. Results on the A-dependence of D meson production have been published in 1994 [15] and these results show no A-dependence of the D-meson production, unlike that of J/ψ production. Reference [16] gave a new world limit for the decay $D^o \rightarrow \mu^+\mu^-$. Future papers still to come will likely be NIM papers on the trigger processor, silicon strip detectors, and the data acquisition system. The h^+h^- data should be fully analyzed during 1995 as well as several other data sets that have not received as much attention as the ones mentioned above.

As mentioned above, the study of the production of charm particles (specifically the J/ψ) at large x_F in p+Cu and p+Be collisions has been published [7, 8]. In a series of theoretical papers[9-12], it has been proposed to explain the suppression of J/ψ production in heavier nuclear targets by the inclusion of what is termed "intrinsic charm". This prompted the E789 collaboration to spend a few days taking data for J/ψ production in the Cu internal beam dump and in a block of Be to check on the large x_F prediction of this model. The differential cross section was measured from $0.30<x_F<0.95$ with the result shown in Figure 3. Predictions for the intrinsic charm contribution to the cross section was estimated to be 1.8 nb/nucleon in Cu and 3.2 nb/nucleon in Be [9,12]. At the 95% confidence level the upper limits for these contributions were found to be $<2.3\times10^{-3}$ nb/nucleon for Cu and $<1.3\times10^{-2}$ nb/nucleon for Be. These results were accurately modeled using the semilocal parton duality model modified to account for parton shadowing in the nuclear target as shown in Figure 3. This model predicts that gluon-gluon fusion dominates the production cross-section at $x_F<0.6$, while quark-antiquark annihilation dominates at $x_F> 0.6$. Figure 4 shows the exponent α of the A-dependence of J/ψ production, where $\sigma = \sigma_0 A^\alpha$. The solid points are from this experiment and the open circles are from E772. Only statistical errors are shown.

The major part of the data taken for E789 were divided into two major data sets. The acceptance of the spectrometer is shown in Figure 5 for three different decay modes as a function of the current in the large SM12 magnet. The two settings indicated in the figure were used to take "charm" and "beauty" data. The silicon vertex detector was used to trigger on events occurring downstream of the target. Figure 6 shows the reconstructed vertex resolution overlaid on the actual size of the 3 mm Au target. In this coordinate system, x is horizonal to the beam axis, y is vertical to the beam axis and z points in the direction of the beam. The Au target in this case was a 3 mm thick, .2 mm high, and 50 mm long strip. As is seen in this figure, the vertex resolution is quite good and should become even better once vertex constrained fitting is added to the reconstruction code. Looking at the bottom plot, one can see the excellent z-vertex resolution. By requiring a vertex to be more than a few mm downstream of the target we have almost completely eliminated events coming from the target. Figure 7 shows the mass spectra of the πK pairs for the p+Be dihadron data for two different lifetime cuts and the p+Au dihadron data for two different magnetic field settings. The value of τ/σ is the number of lifetimes the event occurred downstream of the target. There are two entries per event since the K was not able to be identified. The D meson shows up clearly (the peak is broadened from wrong mass assignment combinations) and no evidence is found for a nuclear dependence of D meson production in contrast to the large suppression seen in J/ψ and ψ' production. The result for D-meson A-dependence production cross section [15] is

$$\alpha = 1.02 \pm 0.06, \text{ where } \sigma = \sigma_0 A^\alpha$$

The B analysis has concentrated on the $B \rightarrow J/\psi X \rightarrow \mu^+\mu^- X$ data. We have 52 candidates for this B decay mode and obtained the doubly-differential cross section for J/ψ mesons originating from b-quark decays, assuming linear dependence on nucleon number, of

$$d^2\sigma/dx_F dp^2_T = 107 \pm 28 \pm 19 \text{ pb/ (GeV/c)}^2.$$

Figure 8 shows the $\mu^+\mu^-$ mass spectrum for the data. Figure 9 shows the mass spectrum for events with their vertices downstream and upstream of the target. The downstream case (top right plot) has 52 events consistent with the hypothesis that we are indeed seeing $B \rightarrow J/\psi X \rightarrow \mu^+\mu^- X$. This result has been eagerly awaited by several other groups planning b-quark experiments and is one of the main achievements of E789.

A proposal was prepared, Fermilab P865, to follow up on the knowledge gained in E789 on measuring rare decays of B mesons. This proposal was to take advantage of a new optical trigger for Beauty proposed by Charpak, Lederman, and Giomataris [13]. The goal was to create a detector optimized for B meson studies, but currently this proposal appears to be evolving into a high rate charm detector which was discussed at the Charm 2000 workshop at FNAL in June of 1994 [17]. Isenhower has worked with D. Kaplan (IIT), C. Brown (FNAL), C. Darden(SC), and M. Atac (UCLA/FNAL) on a Ring Imaging Cherenkov (RICH) detector for particle identification with extremely high rate capability [14]. This device would take advantage of Visible Light Photon Counters (VLPC's) that Atac and others have been working on extensively for the optical trigger for beauty. Such a RICH could have several very useful applications and some work on the ideas behind it may make interesting honors projects for undergraduates at ACU.

References:

1. H. Albrecht et al., Phys. Lett. **B192** (1987) 245; C. Albajar et al., Phys. Lett. **B186** (1987) 247; H. Band et al., Phys. Lett. **B200** (1988) 221.
2. F. J. Gilman, SLAC-PUB-4736, Oct. 1988, Invited talk given at the Heavy Flavor Physics Symposium, Beijing, China, 10-20 Aug. 1988; F. J. Gilman, SLAC-PUB-4955, April 1989, Invited lecture at the Third Mexican School of Particles and Fields, Cuernavaca, Mexico, 5-16 Dec. 1988.
3. D. Alde et al., Phys. Rev. Lett. **64** (1990) 2479.
4. Y.B. Hsiung et al., Phys. Rev. Lett. **55** (1985) 457; J.A. Crittenden et al., Phys. Rev. D **34** 2584 (1986)
5. T. Nakada (editor), *Feasibility Study for a B Meson Factory in the CERN ISR Tunnel*, CERN 90-12, 30 Mar. 1990; (also see *Proposal for an Electron Positron Collider for Heavy Flavour Particle Physics and Synchrotron Radiation*, PSI-PR-88-09 on which the CERN proposal is based)
6. R. Bouclier et al., Nucl. Instr. and Meth. **205** (1983) 403; P. Mangeot et al., Nucl. Instr. and Meth. **216** (1983) 79; H. Glass et al., IEEE Trans. on Nucl. Sci. **NS-30** (1983) 30; M. Adams et al., Nucl. Instr. and Meth. **217** (1983) 237.
7. M.S. Kowitt (Ph.D Thesis), Hadronic Production of J/ψ at Large x_F in 800 GeV p+Cu and p+Be Collisions, LBL-33331, UC-414, December 1992.
8. M.S. Kowitt, et al., Production of J/ψ at Large x_F in 800 GeV p-Copper and p-Beryllium Collisions, Phys. Rev. Lett. **72**, 318 (1994).
9. R. Vogt, S.J. Brodsky, and P. Hoyer, Nuc. Phys. **B360**, 67 (1991).
10. S.J. Brodsky et al., Phys. Lett. **93B**, 451 (1980).
11. S.J. Brodsky, C. Peterson, and N. Sakai, Phys. Rev. D **23**, 2745 (1981).
12. S.J. Brodsky and P. Hoyer, Phys. Rev. Lett. **63**, 1566 (1989).
13. Charpak, Lederman, and Giomataris, NIM **A306**, 439 (1991).
14. D.M. Kaplan, L.D. Isenhower, M. Atac, C.N. Brown and C.W. Darden, FERMILAB-Conf-93/148, paper presented at the 1st Workshop on Rich Detectors, Bari, Italy, June1-5, 1993, published in NIM **A343**, 316 (1994).
15. M.J. Leitch et al, Phys. Rev. Lett. **72**, 2542 (1994).
16. C.S. Mishra et al., Phys.Rev. **D50**, 9-12(1994).
17. *A Fast Ring-Imaging Cherenkov Counter Using Visible Light Photon Counters (Vlpc)*, Donald Isenhower, presented at the CHARM2000 Workshop on The Future of High-Sensitivity Charm Experiments, Fermilab, June 7-9 1994, p. 198, FERMILAB -Conf-94/190.

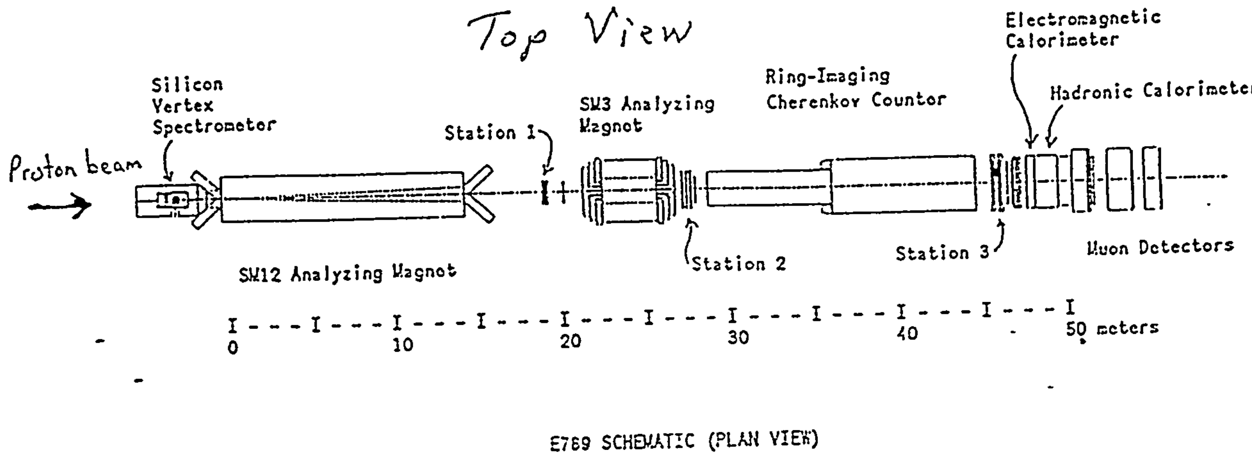


Figure 1

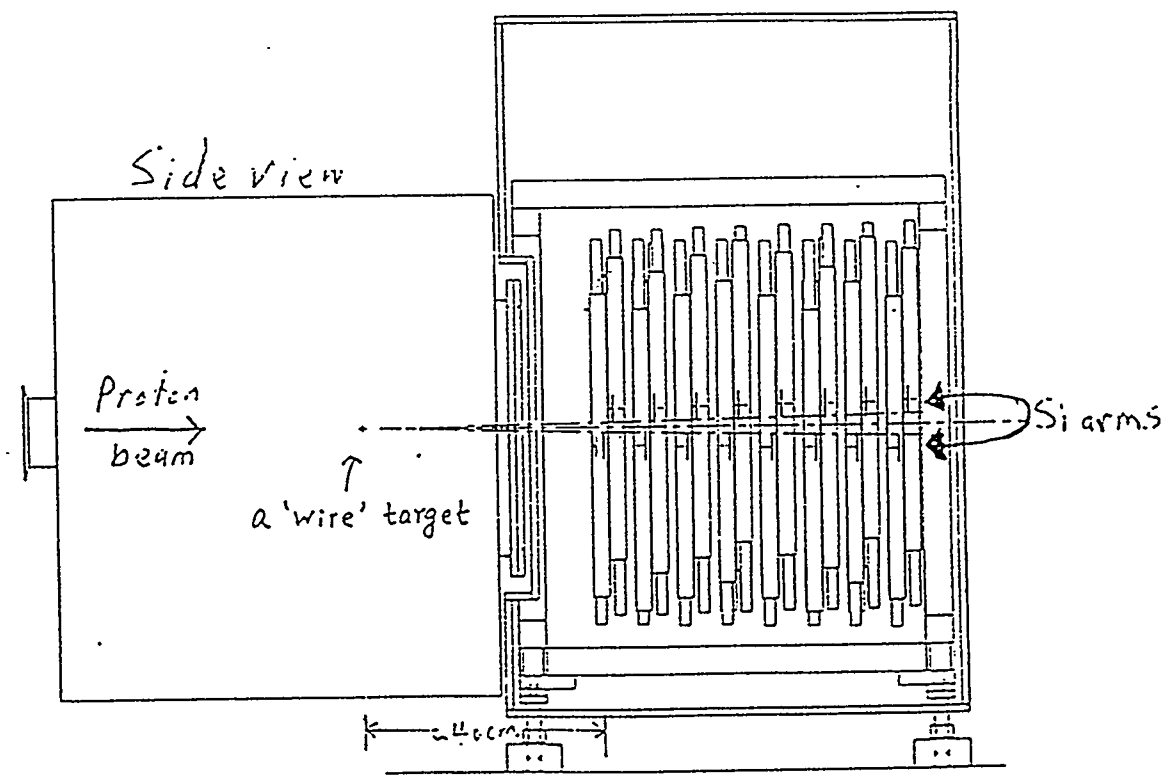


Figure 2

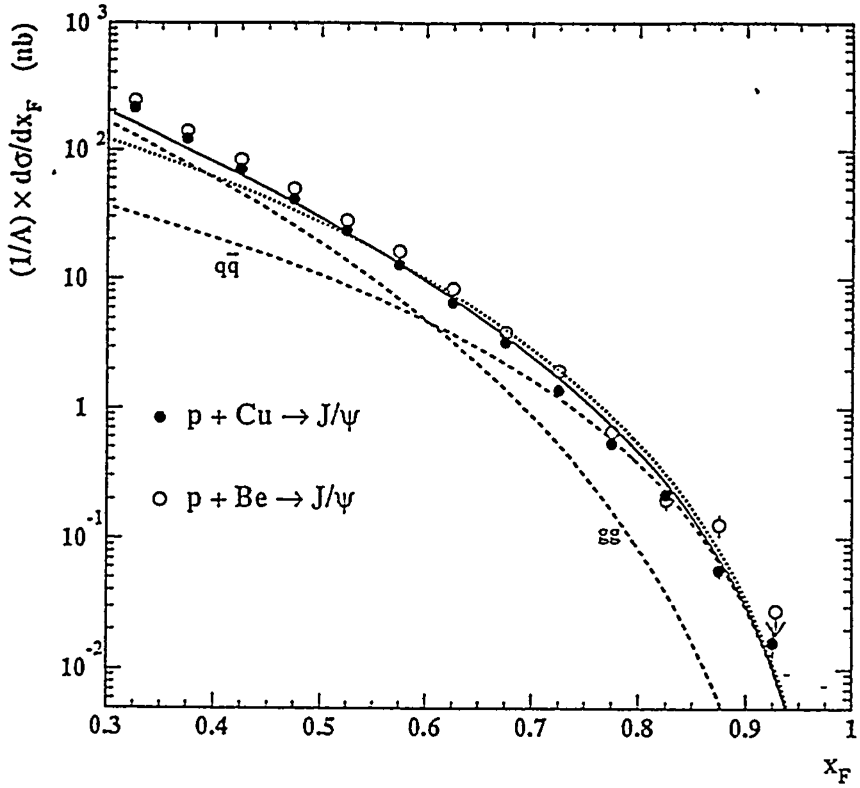


Figure 3

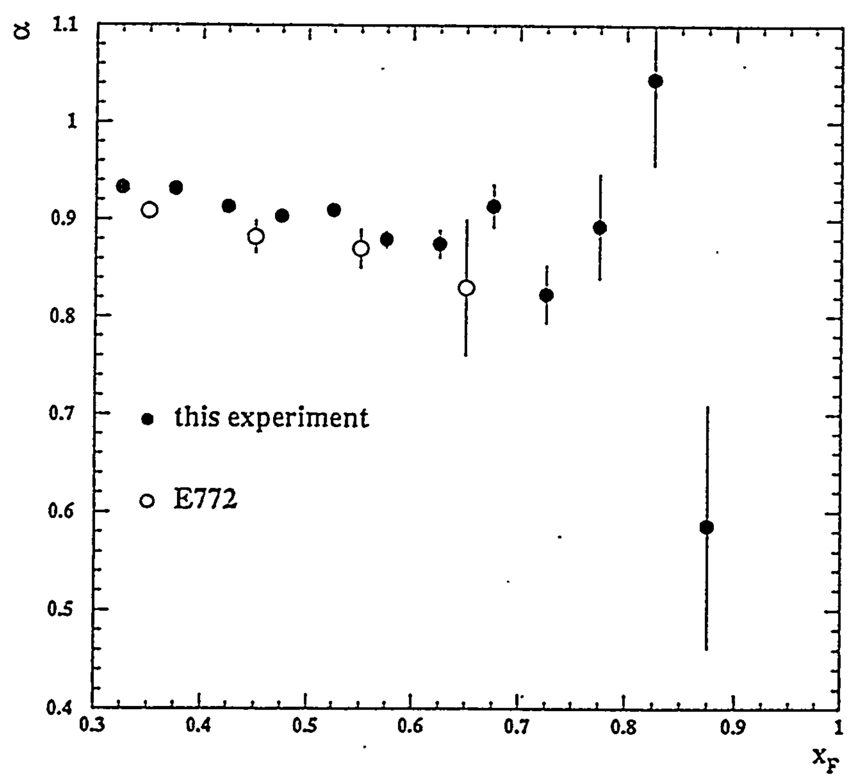
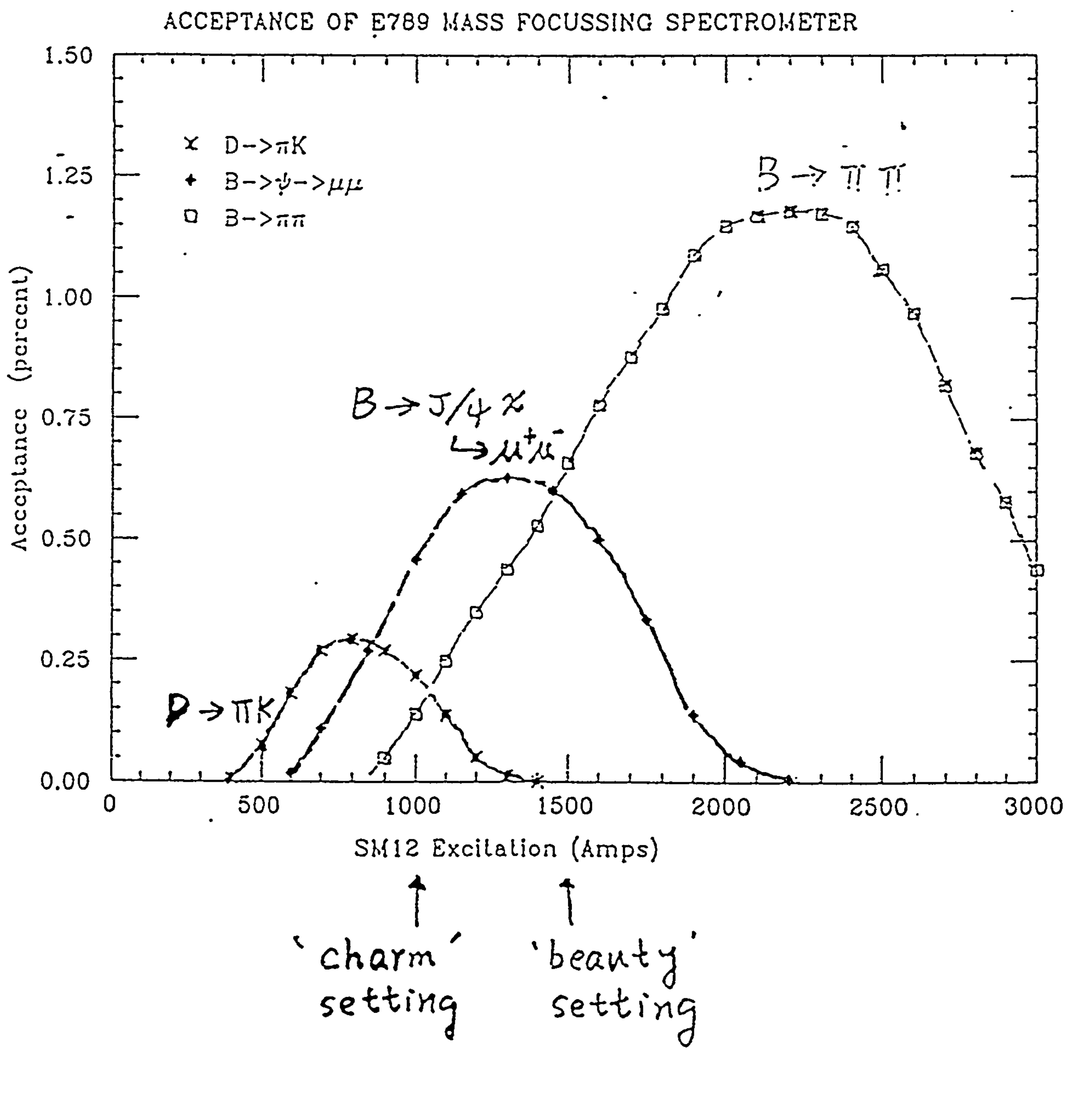
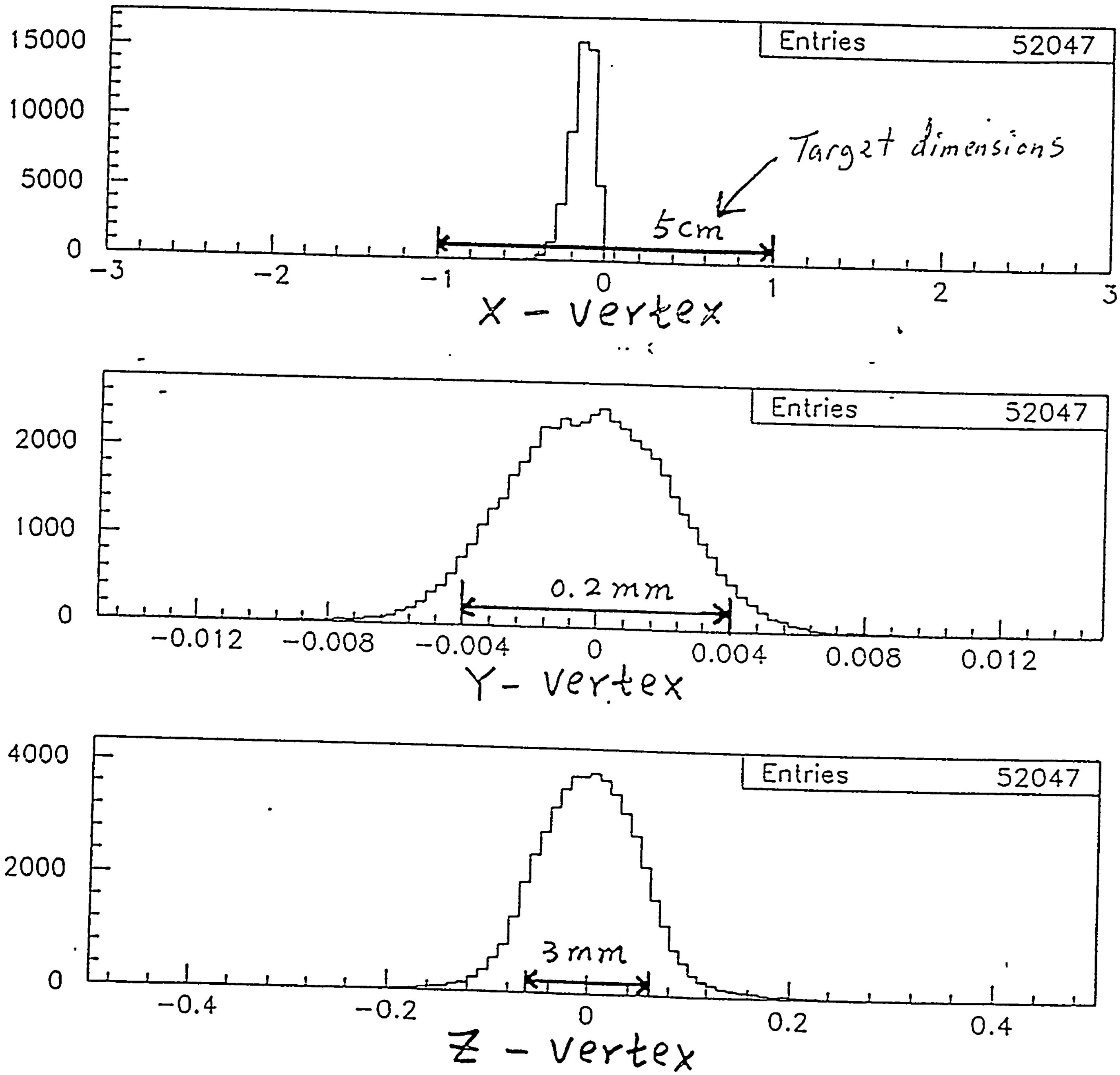


Figure 4



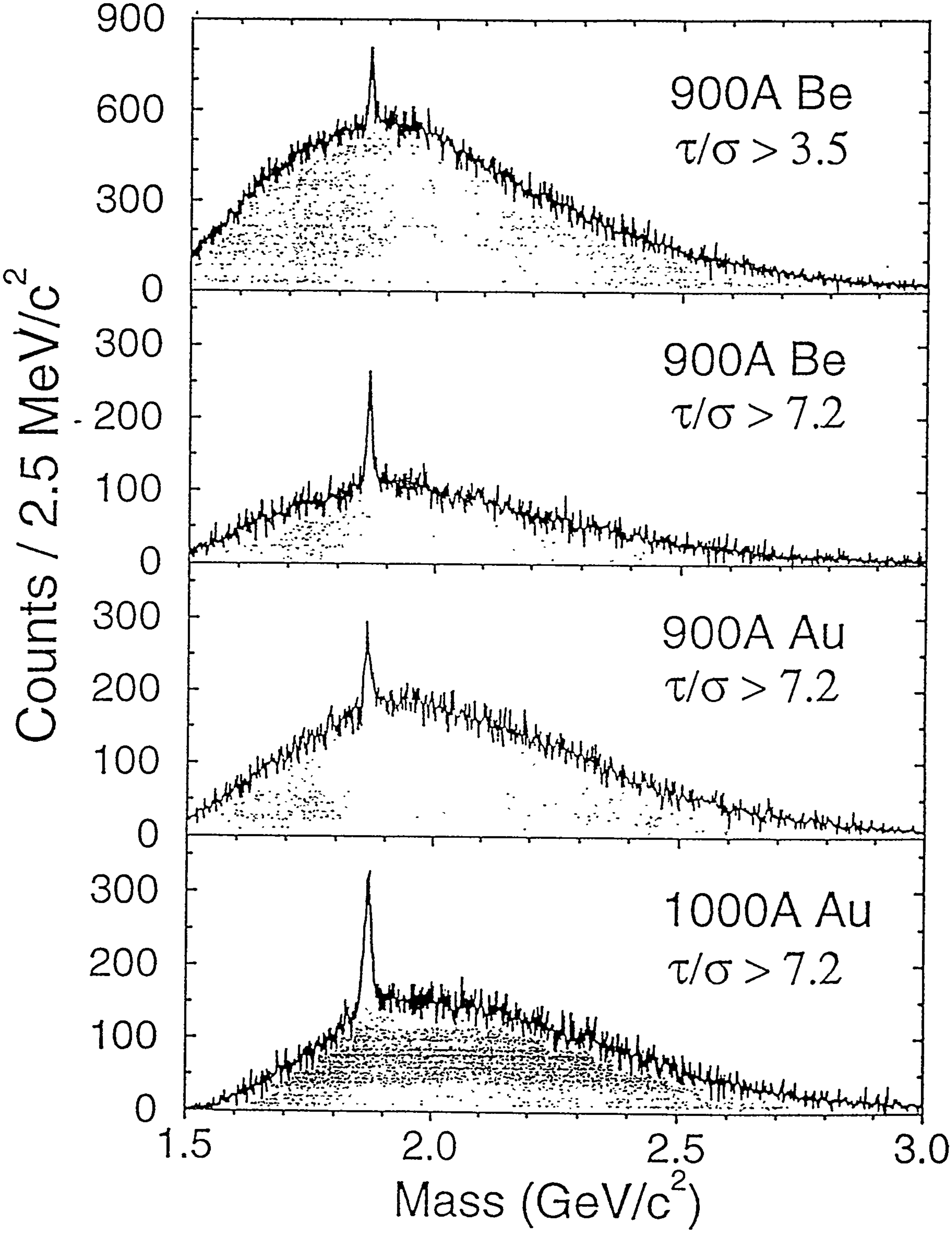
ACCEPTANCE OF E789 MASS FOCUSSING SPECTROMETER
1.50
1.25
1.00
0.75
0.50
0.25
0.00
Acceptance (percent)
D->πK
B->ψ->μμ
B->ππ
B → π π
B → J/ψ X
↳ μ+μ-
D → πK
0
500
1000
1500
2000
2500
3000
SM12 Excitation (Amps)
'charm' setting
'beauty' setting

Figure 5



Average decay length for B-meson (<p> ~ 150 GeV)
is ~ 1.2 cm

Figure 6



900
600
300
0
300
200
100
0
300
200
100
0
300
200
100
0
Counts / 2.5 MeV/c^2
900A Be
τ/σ > 3.5
900A Be
τ/σ > 7.2
900A Au
τ/σ > 7.2
1000A Au
τ/σ > 7.2
1.5
2.0
2.5
3.0
Mass (GeV/c^2)

Figure 7

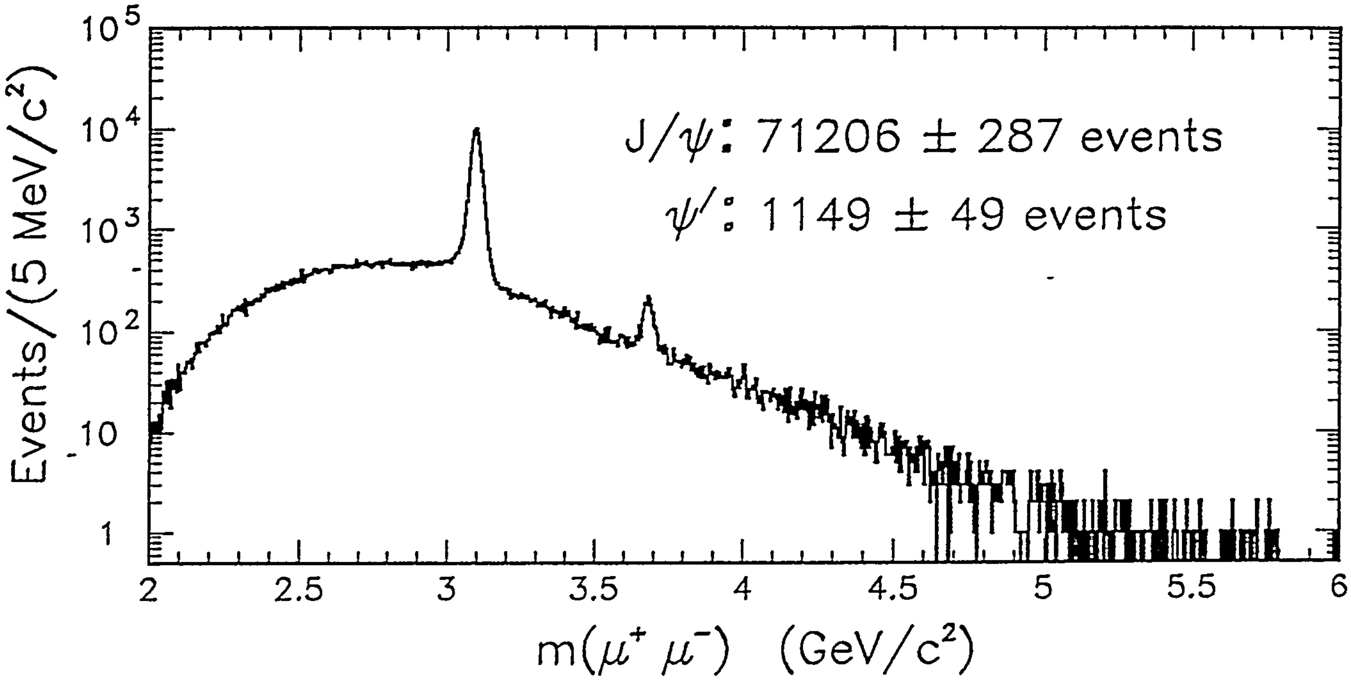


Figure 8

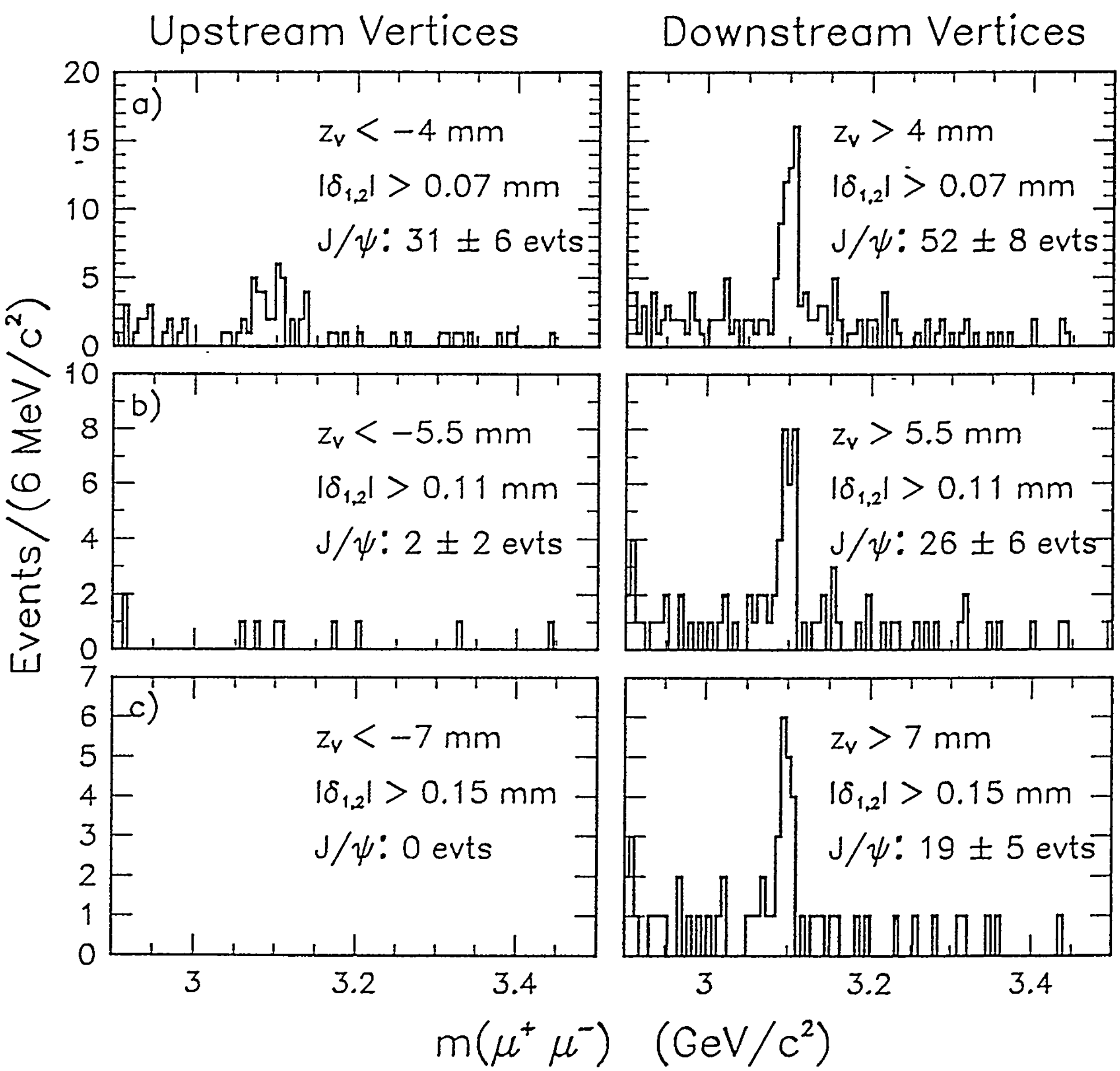


FIG. 3. Dimuon invariant-mass distributions for successively tighter cuts on z_v and on the absolute values of the impact parameters of the two muon tracks $|\delta_{1,2}|$.

Figure 9

B. FNAL Experiment 866: Measurement of $\bar{d}(x)/\bar{u}(x)$ in the Proton

Experiment 866 (E866) is a high statistics measurement of the relative yield of Drell-Yan dimuon pairs from p+p and p+d collisions. The collaboration consists of ACU, Academia Sinica (Taiwan), Argon National Laboratory, Cal. Inst. of Tech., Fermilab, Georgia State University, Los Alamos Nat. Lab. (G. Garvey is the spokesperson for the experiment), Louisiana State University, New Mexico State University, Northern Illinois U., Oak Ridge Nat. Lab., Texas A&M and Valparaiso University. This experiment was given good marks by the DOE Review Panel that met in March 1994 and is being favorably discussed in the long range planning process for the field of nuclear physics currently underway.

E866 is currently scheduled to begin in the spring of 1996. The initial physics plans call for about 3-4 months of running, but with several new ideas proposed recently, it is expected that the experiment will make full use of the entire next fixed-target run at FNAL. This will entail running until the shutdown of the Tevatron to finish construction of the new injector in 1998. Since no other experiment has approval for running in the Meson East hall, such extensions to the running of E866 should pose no problem and some of these ideas are discussed below.

Recent deep inelastic measurements indicate that the integrated probability over Feynman x (x_F) of the anti-d quark in the proton is appreciably greater than that for the anti-u quark. E866 will measure the ratio of these two antiquarks in the proton over the interval $0.03 \leq x_F \leq 0.3$. The $\mu^+\mu^-$ mass range covered will be from 1.5 GeV to 15 GeV for the Drell-Yan pair. It will also measure the ratio of J/ψ ,ψ', and Υ cross sections for p+p/p+d. It will use the E605/E772/E789 spectrometer located in the Meson East area at FNAL. The main modifications from the E789 configuration will involve the removal of the silicon strip vertex detector and installation of a magnet in front of the big dipole magnet (SM12, see Section III.A, Fig. 1).

Data will be taken on 50-cm-long liquid hydrogen (LH2) and liquid deuterium (LD2) targets. The target mechanism is capable of switching between the two targets, plus an empty target vessel, between each beam spill (at FNAL the protons are delivered over a 20 second period once per minute). At an intensity of $2x10^{12}$ protons/spill, the rates that the detectors must handle are quite high. This is one of the reasons the experiment will use the existing E605/E772/E789 spectrometer since it has excellent rate capabilities. The ability to cycle rapidly between the targets will help keep the systematic errors below the 2% goal of the experiment. One of the current concerns on contribution to this systematic error is how many different magnetic field settings will be required to cover the planned x_F range. The Monte Carlo program has been converted to work on a DECstation 5000/200 at ACU so that we can help make studies in optimal magnet settings and other aspects of the experiment. Obviously, the fewer settings chosen, the better the measurement will be.

In addition to the currently planned measurements of the anti-u and anti-d quark content of the proton, there are several other investigations under consideration for E866. Among the ideas being explored are:

- A-dependence at small x_{target}($0.015 < x_{target} < 0.04$) for W/Ca/D targets
- A-dependence at large x_{target}($x_{target} > 0.25$) and/or large p_T ($p_T < 6$ GeV/c)
- Drell-Yan at large x_F
- High mass events utilizing events from the internal Cu beam dump
- Y(upsilon) production at large x_F (This would be a very similar experiment to the E789 J/ψ production experiment on the beam dump discussed in Section III.A and would require only a modification in trigger requirements with no additional beam time)
- Nuclear effects of Y, Y', Y" production
- A-dependence of J/ψ production at negative x_F

For E866, ACU is responsible for maintaining the hodoscopes, which we rebuilt for E789. During the past summer ACU had 5 students involved with rebuilding the Station 1 and 2 hodoscopes. Station 1Y was expanded to 16 counters tall and Station 1X was completely rebuilt to cover the extended Y counters. This was done to get an increase in solid angle of roughly a factor of 2 for the D-Y events of interest. Changes in the hodoscope arrangement were also necessary because E866 will be run in what is termed "closed aperture" setting, whereas E789 was run in "open aperture". This refers to whether or not the SM12 magnet's aperture is filled with absorber. This significant gain in acceptance will permit fewer magnet settings to cover the proposed x_F range, which will simplify data analysis. (one impact of the decision to enlarge the Station 1 detectors is the required enlarging of the high rate drift chambers which are being built in Los Alamos). Also Station 2 was pulled out and repaired.

ACU students have tested many of the ansley cables that had been pulled off the detector at the request of the Tiger Team (who later agreed that their removal was unnecessary, but only after they were uncabled and in some cases extensively damaged in the process). A number of other tasks were also completed to begin to bring the spectrometer back into operation such as preparing the work areas needed to work on the various drift chambers that need to be repaired.

It is currently planned that ACU will supervise 3-4 students in the summer (1995) to finish work on the hodoscopes and recable the detector. Tasks of this type are ideally suited for undergraduates, in that they make a genuine contribution to the experiment, learn the 'nuts and bolts' of the apparatus, and use this knowledge to contribute at a higher level as their involvement with the experiment evolves. ACU has been able to make a very positive impact on experiments by providing manpower for labor intensive tasks.

This is also one of the areas where the program at ACU sorely needs the ability to support graduate students. Of the funding requested for graduate student support, 8 months is for use in 1995 on FNAL E866. The student, Rusty Towell, will spend the summer at FNAL and will move to FNAL full time beginning in January 1996. Rusty was one of the students involved in the previous summer's work, and it is expected that he will play a major role in managing our undergraduate students this summer as well as use E866 as his dissertation topic. To participate in this program, he is attending the University of Texas-Austin for his coursework and Isenhower and Sadler will serve as his advisors. Having someone on site at FNAL full time during the academic year will definitely be helpful in keeping ACU actively involved in this important experiment.

IV. LAMPF Pion-Nucleon Program

A. LAMPF Exp. 882 - Measurements of $\pi^- p \to \pi^o n$ at 10, 20 and 40 MeV

The bulk of the analysis of the data at 0°, 90°, and 180° for LAMPF Exp. 882, measurements of $\pi^- p \to \pi^o n$ at 10, 20 and 40 MeV, has been completed [1][2]. Final publication of these data has been frustrated by several persistent problems. One of the problems was that the 20 MeV, 180° data were definitely off in their normalization and could not be fit by any reasonable Legendre expansion. The main cause of this problem was identified, so that the main problem holding up publication of these data should be solved. One of several complications in this experiment was that three LH2 targets failed during the experiment resulting in data being taken with a mixture of LH2, CH2 and Carbon targets. Another was the majority of the 90° data were taken with an incorrect spacer length, resulting in the asymmetric placement of the K-crate arm of the spectrometer.

Jimmy Redmon, a former ACU undergraduate, has completed a Master's thesis from Texas Tech University on the 90° analysis for Exp. 882. Redmon worked with Brooks, his predecessor at Texas Tech, on many aspects of the 0° and 180° analysis and started working on the 90° analysis two years ago. Presently, he is working on a GEANT simulation as a check of the overall efficiency and solid angle determination for the π° Spectrometer. Currently, all of the data are available to the πN community (partial-wave analysts and efforts involved in determining the πN sigma term), but publication is pending until final checks are made with GEANT. This simulation will also be used for the E849 analysis.

The determination of the differential cross sections for $\pi^- p \to \pi^o n$ from the detection of the γ–γ coincidence in the π° Spectrometer is obtained from

$$\frac{d\sigma}{d\Omega} = \frac{Y\,J}{N(\pi^-)\, N_H\, \Omega(\pi^o)\, \varepsilon(\pi^o)\, \varepsilon_W\, f_{abs}\, F_{\gamma\gamma}\, \tau_L} \tag{1}$$

where Y is yield, J is the Jacobian of the transformation of the cross section from the lab to the c.m. frame, $N(\pi^-)$ is the number of beam particles, N_H is the areal density of hydrogen in the target, $\Omega(\pi^o)$ is the laboratory solid angle acceptance of the spectrometer for the two γ rays, $\varepsilon(\pi^o)$ is the π^o detection efficiency (the probability that both of the gamma rays will convert in one of three converters in each arm), ε_W is the overall wire chamber efficiency for detecting the charged particles emerging from the converter (including the track reconstruction), f_{abs} is the fraction of photons that make it to the spectrometer without first converting in the target, air, or veto counters, $F_{\gamma\gamma}$ is the $\pi^o \to \gamma\gamma$ branching ratio (0.98802) and τ_L is the experimental livetime. The quantities in this equation that are peculiar to detecting neutral mesons are $\Omega(\pi^o)$, $\varepsilon(\pi^o)$, ε_W and f_{abs}. Everything else is determined by standard techniques. The dominant uncertainties in determining the differential cross section follow from three primary terms from Eqn. (1): the yield, the lab solid angle, and the π^o detection efficiency. The yield, or the number of π^o's produced, is determined from the π^o energy histograms which contain the sum of the number of π^o's scattered into particular direction with a particular energy subject to fiducial and X cuts. For the 0° and 180° cases, data runs were taken with LH2, CH2, Carbon, and empty targets. For the 90° case, data runs were only taken with CH2 and Carbon targets. The yields obtained from the empty and carbon target were normalized to and subtracted from the CH2 yields to obtain a net yield that is a result of pure hydrogen, or proton scattering.

The determination of the solid angles for the data at 90° required several modifications of the PIANG program due to the unorthodox geometry used. The two arms of the spectrometer were placed above the target to make measurements at 90°. This geometry was necessitated by the large opening angle between the γ rays from the low-energy π^o's. In addition, the wrong spacer length was inadvertently used for one of the arms, giving an asymmetric geometry which had to be modelled correctly in PIANG to calculate $\Omega(\pi^o)$ in Eqn. (1). A portion of the 90° data at 40 MeV had the correct geometry. These data were used to check that the solid angles were being calculated correctly for the asymmetric geometries.

A calculation of the converter efficiency, including the MWPCs, has been completed using the standard EGS program which simulates the electron-gamma interaction in the converter. The simulation has been run for the various energies of the π^o decay photons. The EGS program determines the converter efficiency from the probability that a gamma ray with a certain energy will convert in the converter and also gives the efficiency with the requirement that the resulting electron-positron shower produces a detectable charged particle in the multi-wire proportional chambers (MWPC's). In order to measure the differential cross sections to the 5% level, the efficiency of the detector must be known to that accuracy. The total efficiency is a function of the wire chamber efficiencies, the Pb-glass converter efficiencies, and the probability of a gamma ray passing through the scintillator/veto in front of the detector. We currently believe that this part of our analysis is correct and indeed it does agree with other experiments who have attempted the same efficiency calculations [3]. However, it is desired to do some modelling of our processes with GEANT and this work is in progress with the help of software used in Ref [3] so that we can refine the Monte Carlo calculations to be certain that everything is correct.

It is emphasized that the solid angle is calculated from PIANG for the absolute measurements. The accuracy of this determination depends on how well the program predicts the reconstructed observables. Other experiments using the fully implemented π^o spectrometer normalize to the "known" $\pi^- p \rightarrow \pi^o n$ cross sections. Extensive comparison of the distributions in scattering angle, γ energy in each arm, $\gamma\gamma$ opening angle, and kinetic energy (reconstructed from the opening angle and energy in each arm) were made to PIANG. A modified version of PIANG that permits the direct overlay of Monte Carlo plots and data plots was implemented. Examples for scattering angle and opening angle distributions for the 20 MeV 90° data are shown in Figures 1 and 2. Here one can see that PIANG is not in complete agreement with the data, and this type of comparison is important to be certain that the solid angles are being calculated correctly. Histograms were created with the following parameter variations: beam energy, beam position in the X and Y direction relative to the target, and target position in the Z direction relative to the pivot between the two arms of the spectrometer. These studies have enabled us to estimate the errors in the final results due to variations in these parameters and have provided insight in our involvement in the design of the NMS.

Results for a full angular range from 0° to 180° are given in Figures 3-5 for energies of 10, 20, and 40 MeV. In Figure 6, the 40 MeV results are shown including the 90° data without the K crate shift. The two sets of data are identical within statistical errors. Each is divided into three distinct regions: forward angle, center angle, and backward angle. Each set is compared to the partial wave analyses of VPI [4] , Karlsruhe-Helsinki [5], and the potential model of Siegel and Gibbs[6]. Also shown is a simple second order Legendre fit to the data. The reduced χ^2 is equal to 1.02, 0.54, and 2.1 for the 10, 20 and 40 MeV data respectively. The data at 11.1 MeV and 21.2 MeV agree very well with the existing analyses. The data at 39.4 MeV are ~15% below the consensus of the analyses near 0°. The difference near 0° is thought to be a consequence of the analyses from Ref. [6] fitting a previous measurement by our group [7], which measured forward-angle cross sections for $\pi^- p \rightarrow \pi^o n$ in the region of the dip near 40 MeV. The ostensible difference in the results is that backgrounds from scattering in air (normalized only to pion flux) were deduced from carbon target runs (which are normalized to both pion flux and the ratio of carbon atoms in the targets) in the previous measurement. Background subtractions for both carbon and blank targets were performed in the present experiment. If only a carbon subtraction is performed for the present data at 39.4 MeV where the cross sections are only 10-20 μb/sr, the present results overlap reasonably well with Ref. [7].

The most important progress in relation to this data is that the large disagreement in the backward angle 20 MeV data has been resolved. The problem had to deal with the method used to measure the pion flux. The data shown in Figure 4 near 180° were normalized based on measurements done while taking the 90° data. The beam tunes were practically identical for these two data sets with the largest difference being that BM03 (third bending magnet in the LEP channel) was 5 Gauss higher for the 180° data. Since the setting was 2866.6 Gauss, this difference cannot change the pion yield more than a fraction of a percent (a 5 Gauss change in BM03 leads to a 70 KeV shift in beam energy, which is also insignificant). It was this feature of our analysis that has caused us to decide that we should first analyze the 90° data before publishing the results at 0° and 180°.

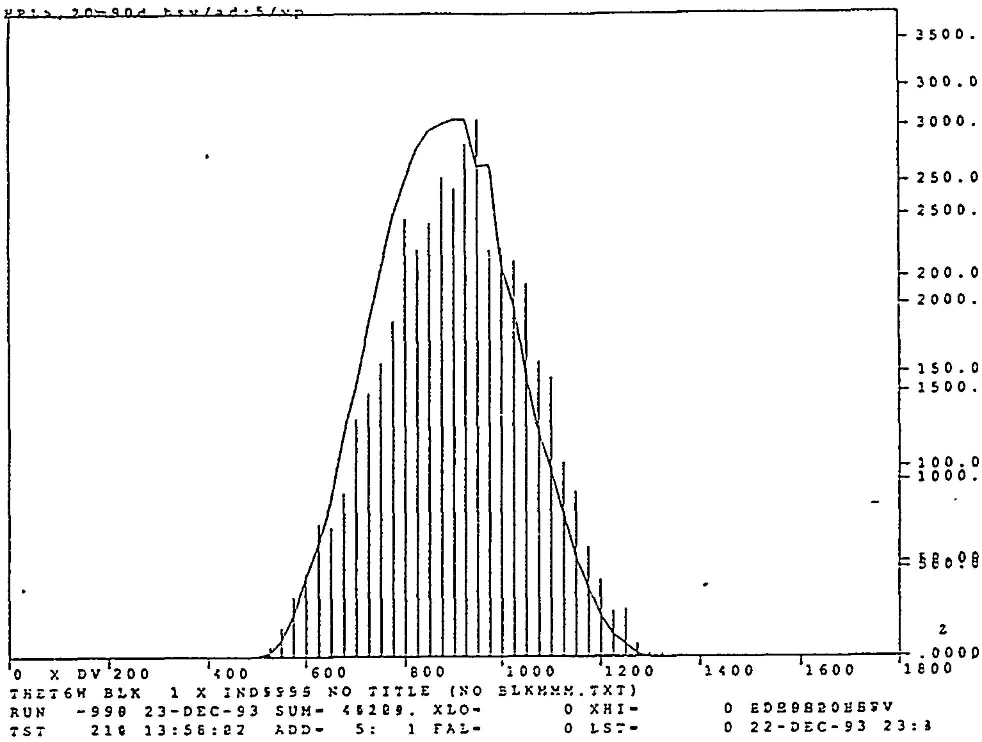


Fig. 1: Measured scattering angle (vert. bars) overlaid on PIANG distribution

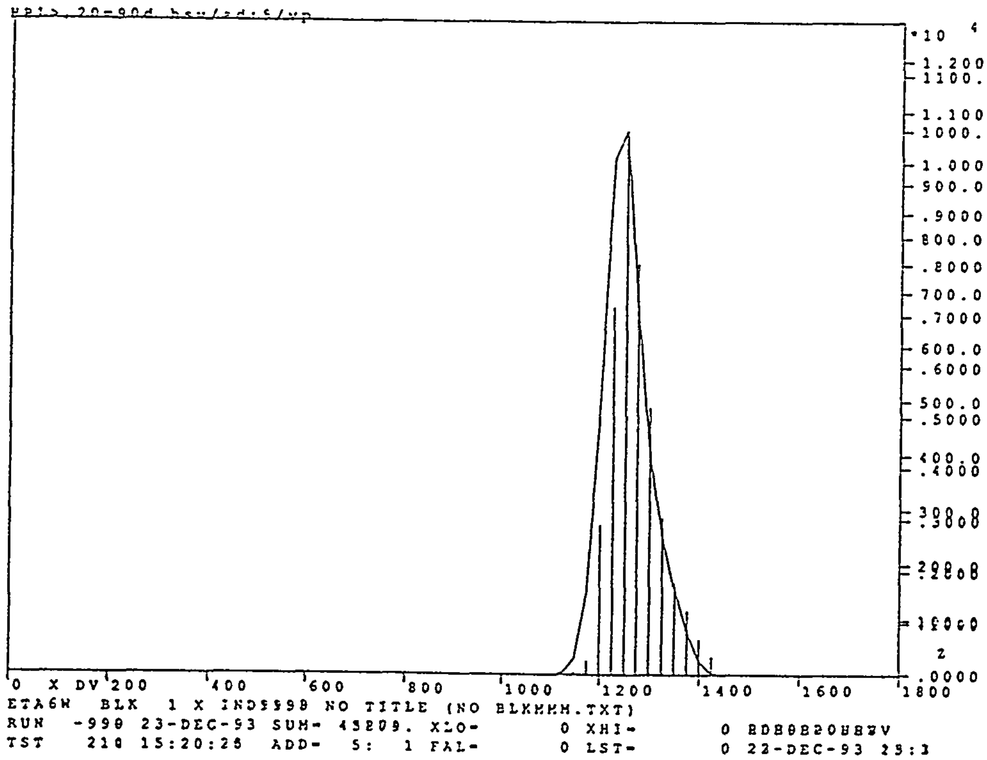


Fig. 2: Measured opening angle (vert. bars) overlaid on PIANG distribution

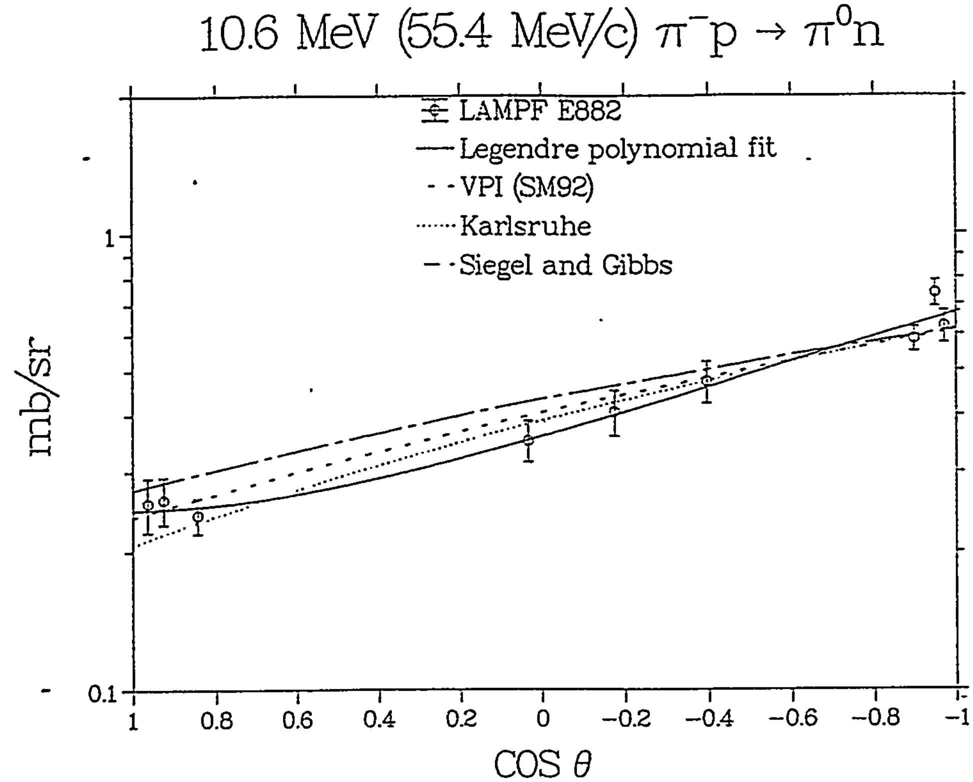


Fig. 3: Differential cross sections from E882 for 10 MeV data (statistical errors only).

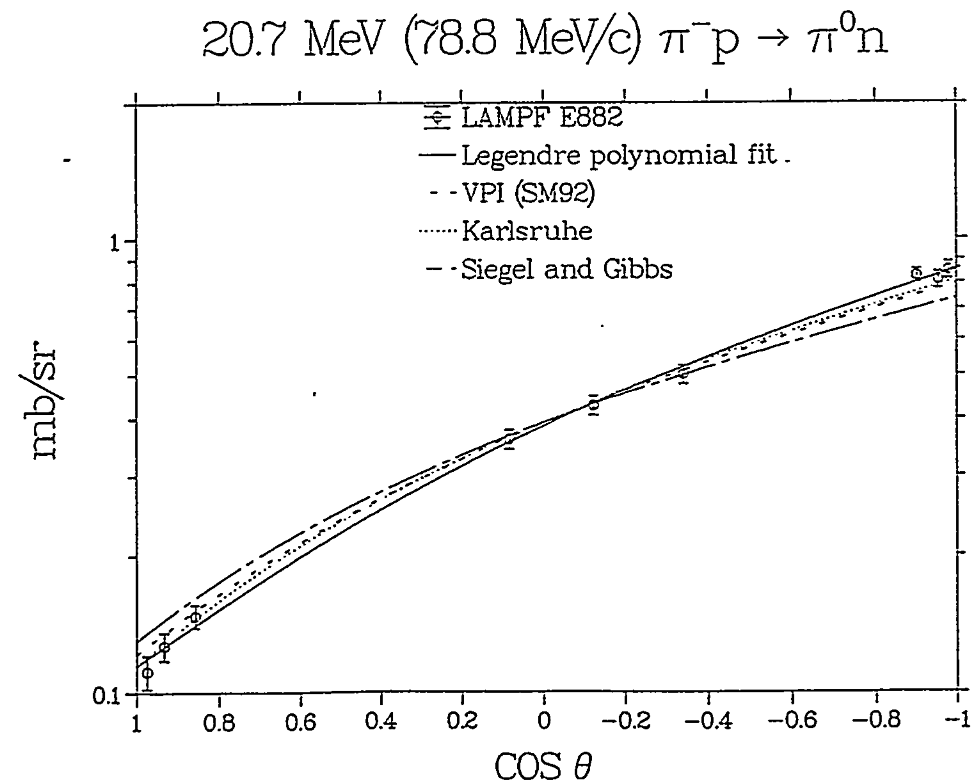
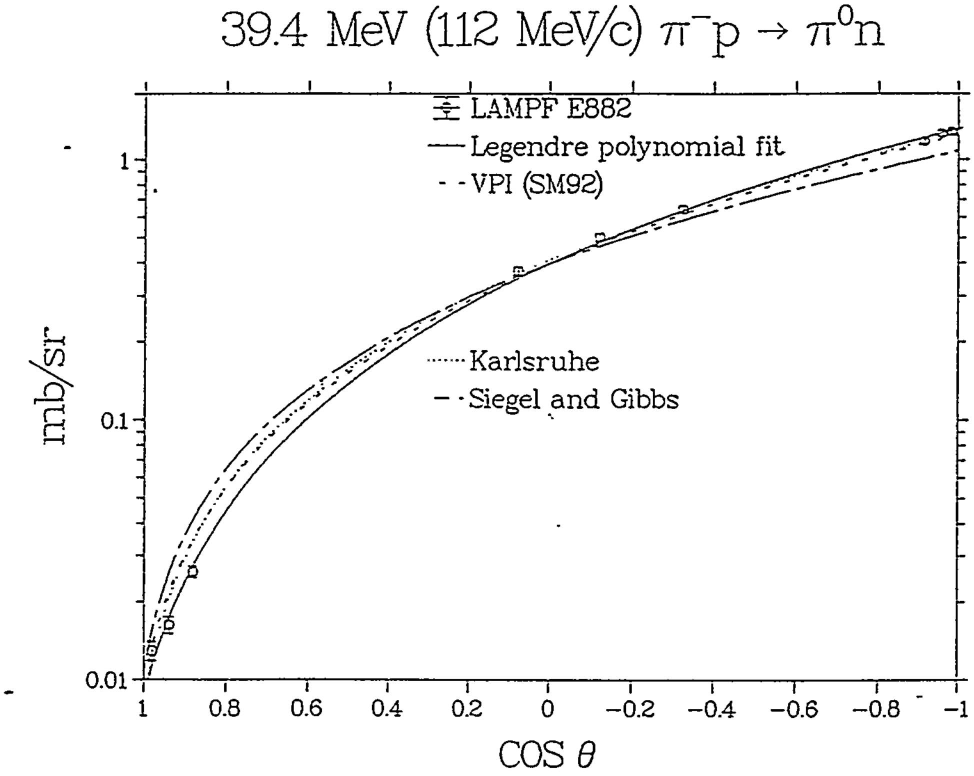


Fig. 4: Differential cross sections from E882 for 20 MeV data (statistical errors only).



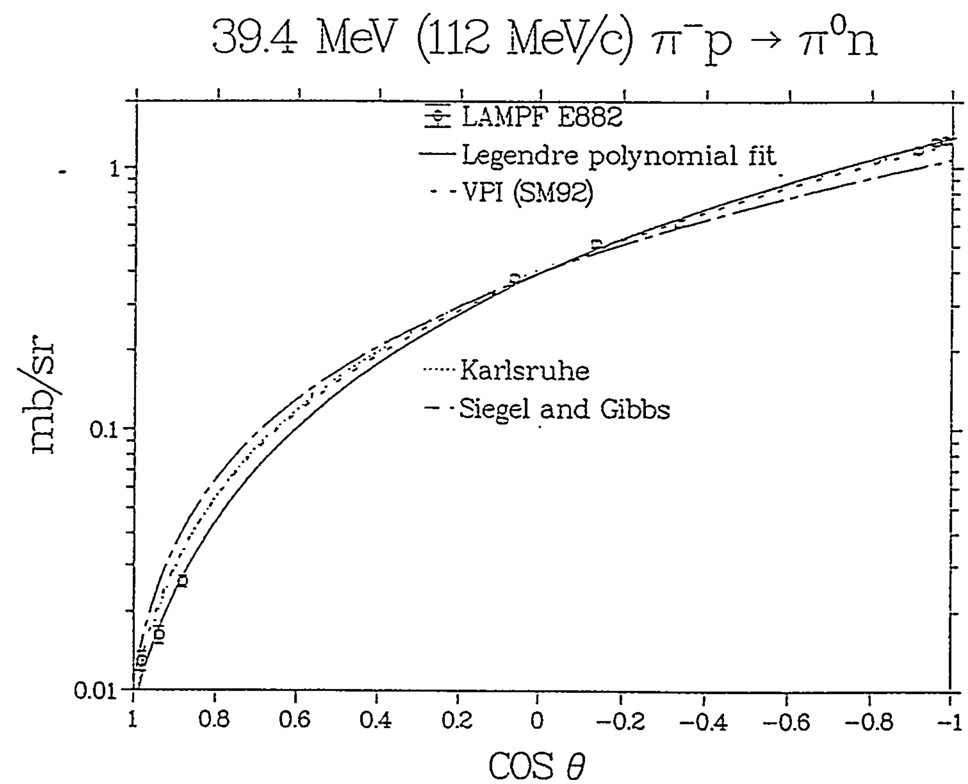


Fig. 5: Differential cross sections from E882 for 40 MeV data (statistical errors only). The bottom plot is the same as the top except for the 90° data, as explained in the text.

B. LAMPF Exp. 1268 $\pi^- p \rightarrow \pi^o n$ Cross Sections in the Region of the Δ Resonance Using the NMS Spectrometer

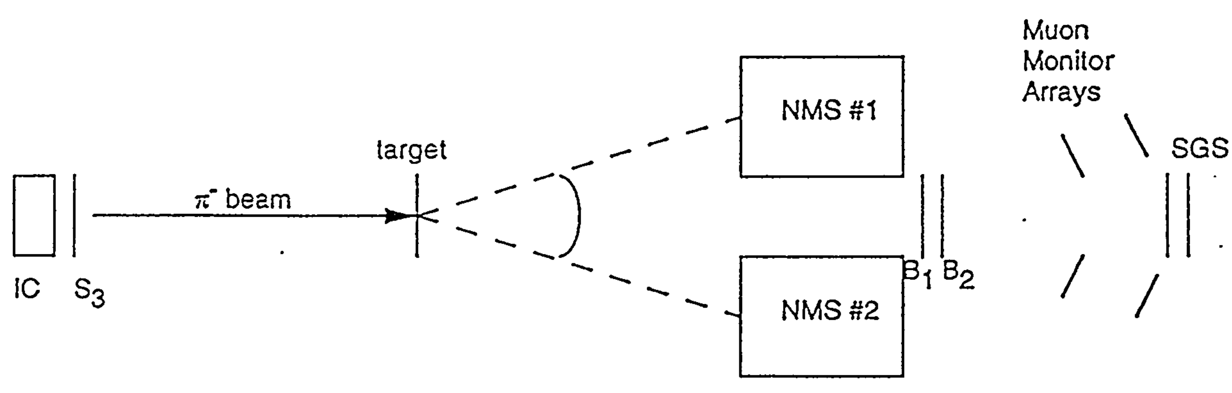
Analysis of Exp. 1268, *$\pi^- p \rightarrow \pi^o n$ Cross Sections in the Region of the Δ Resonance* (M. E. Sadler, spokesperson), is in progress. The data replay is being done by Linh Nguyen-Tansill, a graduate student at Catholic University of America, as part of her Ph.D. thesis. Scientists from Arizona State University, Catholic University of America, University of Colorado, George Washington University, LAMPF, New Mexico State University, University of Pennsylvania, Rudjer Boskovic Institute, and the Petersburg Nuclear Physics Institute collaborated in the measurement phase that was completed in September 1993.

This experiment was the first to use the new Neutral Meson Spectrometer (NMS) in the normal coincidence mode. The program discussed in the previous section using the π^o spectrometer to measure absolute cross sections for $\pi^- p \rightarrow \pi^o n$ led to an active involvement in the development of the NMS at LAMPF. The NMS is based on the same principle as the π^o spectrometer, but improves the energy resolution, vertex resolution of the conversion point of the γ rays, data acquisition rate, solid angle, and versatility. A distinct advantage of the NMS over its predecessor will be better efficiency determination for the γ conversion process and track reconstruction using the wire chambers, a necessity for any fundamental measurement that has to determine its own normalization such as those described in the preceding section.

A specific area that is planned as a project for an undergraduate student is the analysis of the beam monitoring data. The beam monitoring system sketched in Fig. 1 was used to determine the pion flux by normalizing secondary monitors to the beam counters (S_3 and a $B_1 \bullet B_2$ coincidence). The normalization consisted of determining the monitor ratios at low beam rate where the beam counters are reliable. The secondary monitors consisted of an ion chamber (IC), muon monitor arrays and sampling grid scintillator (SGS). The muon monitor arrays, coincident pairs of scintillation counters, were placed to be sensitive to muons from the decay of beam pions. The SGS was also used to measure the electron contamination by TOF with respect to the rf pulses of the accelerator. In addition, activation runs (measurements of the induced ^{11}C activity using calibrated disks of plastic scintillator placed in the beam) were done for all beams as a cross check on both the flux and contamination determinations. An ion chamber (IC) was placed upstream of the target.

The rate dependence of the monitor/beam counter ratio was measured for every beam and detector geometry. There is a sizable volume of data to be compiled and fit to a function which is extrapolated to zero rate (details are given in Ref [8]). Several activation measurements were also made for each configuration. Weighted averages of the results will be obtained and compared to the beam monitors for consistency.

Preliminary results at $T_\pi = 190$ MeV are shown in Fig. 2. The error bars are statistical only. The data show the results that were obtained near $\theta_{cm} = 0°$, 90° and 180°. Other data were obtained near cos $\theta_{cm} = \pm 0.5$, but the original 8-mm data tape was damaged upon the first attempt to copy it. This tape has just been recovered by Advanced Data Recovery of Medford, OR. Unfortunately, Ms. Nguyen is not planning to include these data as part of her thesis as she is planning on a May graduation.



Beam Monitoring Schematic for LAMPF Exp. 1268

Figure 1. Monitor system for the beam normalization of Exp. 1268

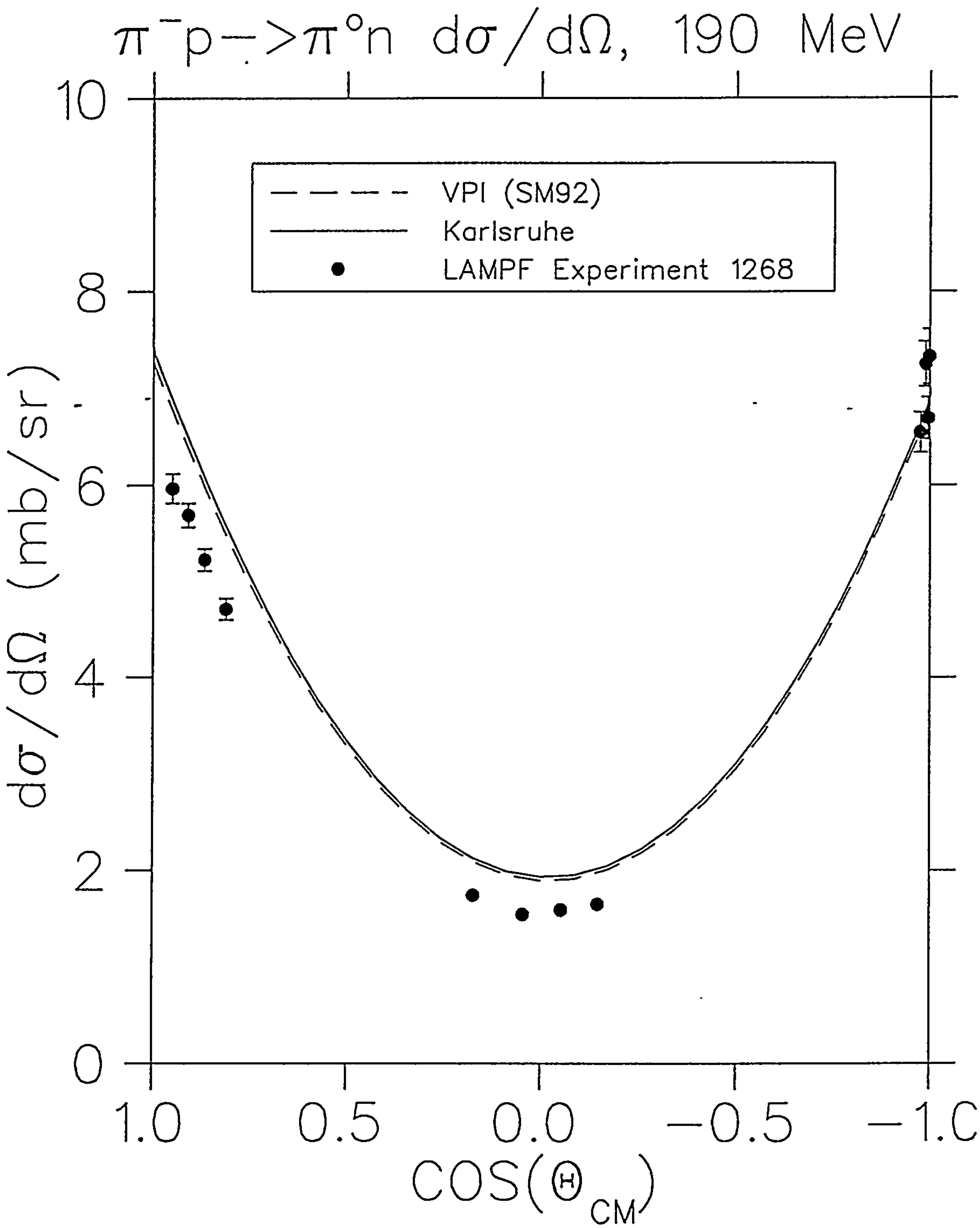


Figure 2. Preliminary results from Exp. 1268 at 190 MeV

C. Low-Energy Analyzing Powers, LAMPF Exp. 1178 and 1256

ACU is a collaborator on two approved experiments at LAMPF to measure polarization asymmetries for $\pi^- p \rightarrow \pi^o n$ (Exp. 1178) and $\pi^\pm p \rightarrow \pi^\pm p$ (Exp. 1256) at low energy. Both of these proposals were given 'A' priority by the LAMPF PAC. Running these experiments has been frustrated by the inability to schedule simultaneously the LEP channel, polarized target and the appropriate detector (the NMS for $\pi^- p \rightarrow \pi^o n$ or the Large Acceptance Spectrometer, LAS, for $\pi^\pm p \rightarrow \pi^\pm p$). As of this writing, it appears that Exp. 1178 will run during August and September of 1995. The NMS and a transversely polarized are presently being installed in the LEP channel.

Spokespersons for Exp. 1178 are J. R. Comfort (Arizona State) and G. Burleson (New Mexico State). The energy range proposed is 45 to 190 MeV. No published measurements of the analyzing power for $\pi^- p \rightarrow \pi^o n$ exist below 190 MeV[9], the lowest energy measured by the UCLA-ACU-GWU collaboration. In combination with cross-section data, these measurements provide important information on the relative phases between the spin-independent and spin-dependent terms in the effective pion-nucleon interaction. Data at low energies (e.g., 45 MeV) are very sensitive to small changes in the P_{11} phase. The data will help to resolve existing discrepancies in the πN data base at low energies and associated problems in phase-shift analyses.

The data will also be useful for constraining extrapolations of the πN amplitudes to the unphysical Cheng-Dashen point for extraction of the πN σ term. Although this quantity involves an isoscalar matrix element, one must extract the isoscalar values from the isospin-3/2 and -l/2 information in πN scattering. The isospin-3/2 portion is determined by $\pi^+ p$ scattering. The isospin-1/2 contribution must be determined from $\pi^- p \rightarrow \pi^- p$ elastic scattering, which is dominated by Coulomb effects at very low energies, or $\pi^- p \rightarrow \pi^o n$ charge exchange.

Comfort and Burleson are also the active spokespersons for LAMPF Exp. 1256, *Measurements of the Analyzing Powers for $\pi^\pm p \rightarrow \pi^\pm p$ at 45 and 67 MeV*. At the time the experiment was proposed, there were no measurements below 90 MeV of these analyzing powers. Preliminary data from PSI now exist[10]. The main difficulty with this experiment is the need to detect low-energy charged particles escaping the polarized target material, cryostat, and magnetic field. There are substantial disagreements between differential-cross-section measurements at nearby energies, as well as between several of the data sets and the results of calculations from current phase-shift solutions. The situation has been discussed extensively, for example by Siegel and Gibbs[11], Sadler[12], Bagheri, et al.[13], and Hill[14]. Tony Hill, the author of Ref. [14], is a former ACU undergraduate.

Locher and Sainio[15] have shown that measurement of the analyzing powers in this energy range can significantly affect the determination of the pion-nucleon sigma term. They state:

> We conclude that precision experiments determining the differential cross section and polarization around $T_\pi = 50$ MeV should well be able to resolve the present discrepancy between the solutions based on low energy scattering data and on mesic atoms level shifts resolving thus the ambiguity in the determination of the sigma term.

The energies for Exp. 1256 were selected because of this conclusion and the existence of measurements of the differential cross sections at these energies at both TRIUMF[16-18] and PSI[10].

Both of these experiments will use a dynamically polarized target and a dilution refrigerator to "freeze" the spin, allowing the field to be reduced to 0.5 Tesla. Frozen spin is essential to measuring analyzing powers at low energy in order to keep the bending of the incident and scattered pions to an acceptable level. A backup plan for this summer's running is to use a conventional target for Exp. 1178 if for some reason the target cannot be run in frozen spin mode.

References for Section IV:

1. B. M. Brooks, Texas Tech thesis, 1992 (unpublished).
2. J. R. Redmon, Texas Tech thesis, 1994 (unpublished).
3. Emil Frlez, University of Virginia Ph.D dissertation, May 1993 (unpublished).
4. R.A. Arndt, J.M. Ford and L.D. Roper, Phys. Rev. **D32**, 1085 (1985), updated periodically in the SAID program.
5. R. Koch and E. Pietarinen, Nucl. Phys. **A336**, 331 (1980).
   R. Koch, Nucl. Phys. **A448**, 707 (1986).
   G. Höhler, Landolt-Börnstein Vol. **I/9b**, Springer-Verlag (1983).
6. P. B. Siegel and W. R. Gibbs, Phys. Rev. **C33**, 1407 (1986).
7. D. H. Fitzgerald, et al., Phys. Rev. **C34**, 619 (1986).
8. M. E. Sadler, et al., Phys. Rev. **D35**, 2718 (1987).
9. G. J. Kim, et al., Phys. Lett. **B219,** 62 (1989), and Phys. Rev. **D41**, 733 (1990).
10. C. Joram, et al., Proc. of the 5th Int. Symp. on Meson-Nucleon Physics and the Structure of the Nucleon, Vol. I, held at Boulder, CO, September 6-10, 1993 (G.

Höhler, W. Kluge and B.M.K. Nefkens, ed.).
11. P. B. Siegel and W. R. Gibbs, Phys. Rev. **C33**, 1407 (1986).
12. M. E. Sadler in Physics with Light Mesons and the Second International Workshop on πN Physics, Los Alamos National Laboratory Report LA-11184-C, 200 (1987).
13. A. Bagheri, *et al.*, Phys. Rev. **C38**, 885 (1988).
14. T. S. Hill, Journal of Undergraduate Research in Physics, Vol. **9**, No. 2, 53 (1991).
15. M. P. Locher and M. E. Sainio, PSI preprint PR-88-17 (1988).
16. J. T. Brack, et al., Phys. Rev. **C34**, 1771 (1986).
17. J. T. Brack, et al., Phys. Rev. **C38**, 2427 (1988).
18. J. T. Brack, et al., Phys. Rev. **C41**, 2202 (1990).

V. Russian Collaborations

ACU has entered into two new agreements with the Meson Physics Group at Petersburg Nuclear Physics Institute (PNPI), S. P. Kruglov, head. These agreements are included below. The first agreement is to continue the collaboration, now called CUSPP (Collaboration of United States and Petersburg Physicists). Although no new involvement by ACU physicists is anticipated at PNPI, the agreement provides the group the use of a qVt multichannel analyzer, NIM bin, and a subset of the constant fraction discriminators and CAMAC TDC's that were purchased for the measurements discussed in the progress report.

The second agreement is specifically for participation by PNPI scientists in the experimental program at BNL. Russian participation is particularly needed for the present experiments (E890 and E909) as well as for the planned baryon spectroscopy program with the Crystal Ball. The proton running at the AGS is apparently scheduled during January-May until RHIC comes on line, making it very difficult for academic scientists from ACU, UCLA and GWU to participate. An increase in the budget request for this year is to cover per diem and travel expenses by participating physicists from PNPI.

A G R E E M E N T

between the Petersburg Nuclear Physics Institute and Abilene Christian University to perform joint experiments by "CUSPP", the Collaboration of United States and Petersburg Physicists

In accordance with paragraph (ITEM) 26 the USA-Russia program "Fundamental Properties of Matter" (programs for CY 1991, CY 1992, CY 1993, CY 1994 of JCC-FPM), experiments investigating the $\pi^- p$ reaction in the region of the $P_{33}(1232)$, $P_{11}(1440)$ and $S_{11}(1535)$ resonances are underway at the Petersburg Nuclear Physics Institute (PNPI). We plan to use in 1994-98 for these experiments the facilities for Intermediate Energy Physics at PNPI, the Clinton P.Anderson Meson Physics Facility at Los Alamos (LAMPF) and Brookhaven National Laboratory (BNL).

The experiments by CUSPP are to be performed by scientists from PNPI, University of California at Los Angeles (UCLA) and Abilene Chistian University (ACU). It is planned to study the reaction $\pi^- p \to \pi^\circ n$ in the energy range of the $P_{33}(1232)$, $P_{11}(1440)$ and $S_{11}(1535)$ resonances and the reaction $\pi^- p \to \eta n$ in the energy range of the $P_{11}(1440)$ and $S_{11}(1535)$ resonances. At present, pion beams available at PNPI, LAMPF and BNL are suitable for measurements in this energy range.

Professors M.E.Sadler and L.D.Isenhower and students from ACU, Professor B.M.K.Nefkens and his group from UCLA, and the Meson Physics Laboratory at PNPI (Dr. S.P.Kruglov, head) will participate in the program.

Abilene Christian University will provide for experiments at PNPI a LeCroy qVt multichannel analyzer, up to 48 channels of CAMAC time to digital converters, constant-fraction discriminators, and NIM-standard electronics bin. All apparatus mentioned above will be returned to ACU after the completion of the experiments or expiration of the agreement, whichever occurs first.

ACU will cover living expenses, accommodations and transportation for PNPI scientists taking part in experiments at LAMPF, BNL and in data analysis and discussions in Abilene.

The Petersburg Nuclear Physics Institute is responsible for targets, gamma detectors, electronics, high voltage power supplies and computers for data acquisition for experiments in Russia. PNPI will provide necessary beam time in accordance with the proposal SC-147 accepted by the PNPI scientific Council. PNPI will cover living expenses, accommodations and transportation (in Russia) for US scientists visiting Petersburg for participation in the experiments. The agreement will start in January, 1994. The experiments will be performed during the next four years.

For the Petersburg Nuclear Physics Institute	For Abilene Christian University
A.A. Vorobyov	Dwain Hart
Director of High Energy Physics Division of PNPI	Vice President for Academic Affairs
S.P. Kruglov	Michael Sadler
Head of the Meson Physics Laboratory	Professor of Physics
	29 December, 1993

AGREEMENT

between

University of California at Los Angeles,
Abilene Christian University, and
Petersburg Nuclear Physics Institute
to perform joint experiments at
Brookhaven National Laboratory.

In accordance with the US/Russia general program "Fundamental Properties of Matter" (items 2-I and 26 of program for CY 1995 which was approved on 17th session of the JCC-FPM in August 1994), an experimental program is in progress and future experiments are planned at the Alternating Gradient Synchrotron (AGS) at the Brookhaven National Laboratory. The experiments include investigating eta (η) production in the reactions $\pi^{\pm}d \rightarrow \eta NN$, $\pi^- p \rightarrow \eta n$ and $K^- p \rightarrow \eta\Lambda$ (Experiments #890 and #909, presently underway at the AGS). The experiments on the subject of "Physics with Light Mesons" are being performed by scientists from Brookhaven National Laboratory (BNL), the University of California at Los Angeles (UCLA), Abilene Christian University (ACU), the Petersburg Nuclear Physics Institute (PNPI) and other Universities and Institutes.

In 1995-1996 we plan to perform Experiments #890 and #909 at the BNL AGS along with the associated data processing and analysis. The goal of the experiment to measure $\pi^{\pm}d \rightarrow \eta NN$ is to search for a violation of charge symmetry. The primary goal for the measurements of $\pi^- p \rightarrow \eta n$ and $K^- p \rightarrow \eta\Lambda$ near threshold is to determine the ηn and $\eta\Lambda$ scattering lengths.

Future plans for the collaboration include the measurement of $\pi^- p \rightarrow \gamma n$, $\pi^- p \rightarrow \pi^\circ n$, $\pi^- p \rightarrow \eta n$, $\pi^- p \rightarrow \pi^\circ\pi^\circ n$, and $K^- p \rightarrow \eta\Lambda$ (plus other neutral states that decay into γ rays) at momenta from 0.5 to 1.9 GeV/c. The Crystal Ball detector, presently at SLAC, is planned for these and other measurements, pending approval by the Program Advisory Committee at BNL. The primary goal is to provide better data for the determination of the masses, widths and decay modes of the excited states of nucleons and hyperons.

The Brookhaven National Laboratory provides necessary beam time on the BNL accelerator and equipment and services for approved experiments, as confirmed in the attached letter from Robert Chrien. The University of California at Los Angeles provides for these experiments part of the computer hardware and development of the software for data acquisition, four neutron detectors together with their stands and veto counters, and most of the electronics and photomultiplier tubes for beam monitoring. Abilene Christian University provides part of the electronics and scintillation counters for beam monitoring. ACU and UCLA cover in part (from grants from the U. S.

Department of Energy) the living expenses, accommodation and transportation in the USA for PNPI scientists taking part in experiments at BNL and in data processing and analysis in the USA.

The Petersburg Nuclear Physics Institute provides the "tagged eta meson" facility in Gatchina for testing equipment for the experimental program at BNL. PNPI is responsible in part for data processing and Monte-Carlo simulation (using the GEANT code) on computers at PNPI. PNPI covers living expenses, accommodations and transportation (while in Russia) for US scientists visiting PNPI in Gatchina.

ACU and PNPI together will continue the development of the technique for an independent determination of the beam momentum near the threshold for $\pi^- p \rightarrow \eta n$ (685 MeV/c) using the UCLA neutron counters and the TOF technique.

This agreement starts in February 1995 and covers the two-year period to February 1997.

Feb. 10 '95

B. M. K. Nefkens
Principal Investigator
Particle Physics Research Group
University of California at Los Angeles

10 Feb 1995

Michael E. Sadler
Co-principal Investigator
Particle Physics Group
Abilene Christian University

S. P. Kruglov
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A. A. Vorobyov
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Department of Physics

February 10, 1995

Dr. S. P. Kruglov
Head, Meson Physics Laboratory
St. Petersburg Nuclear Physics Institute
St. Petersburg, Russia

Dear Dr. Kruglov:

This letter endorses the participation of members of your group in the ongoing Experiments E890 and E909 at the Brookhaven Alternating Gradient Synchrotron (AGS). These experiments concern aspects of the mesonic production of eta mesons and the properties of the eta meson in nuclear matter. Your group members are accorded all the privileges of AGS users and are able to use the necessary equipment and services for the execution of the experiment. We value their participation and consider it essential to the successful completion of this research.

Please accept my warmest regard and good wishes.

Sincerely yours,

Robert E. Chrien

Robert E. Chrien, Senior Scientist
Medium Energy Group Leader

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VI. Student Involvement

A. Undergraduate student involvement

The involvement of undergraduates in research is one of the strengths of the program at ACU. It is what has allowed the physics department at ACU to recruit exceptional students and will continue to be important to the principal investigators. DOE funding of the research program at ACU has helped the department's undergraduate program to be recognized as an "exemplary program" by the Southern Accreditation Association. Such recognition makes the university much more supportive of our research program and helps them to see the need to provide services such as computer and network support.

The 20 months support of undergraduate students requested in this renewal is enough to employ 5-6 students full time during the summer and leave a little support for work during the academic year. Academic year work is subsidized by internal ACU Research Council Grants at a level of approximately $6,000 /year for the combined grants of the two principal investigators. This number of summer students can be properly supervised where both the investigators and the students benefit from this participation. These students will continue to be encouraged to present papers at regional APS meetings and to work on senior honors thesis projects on projects related to the proposed research program in this renewal.

B. Graduate student involvement

ACU does not have a graduate program on campus, but there are two programs where it is possible for the principal investigators to serve as thesis advisors for M.S. and Ph.D candidates. One program has been conducted in cooperation with Texas Tech University. Sadler is an adjunct faculty member of Texas Tech and has served as the thesis advisor for Meade Brooks and James Redmon, both of whom obtained M.S. degrees on LAMPF E882.

Due to recent decisions by the physics department at Texas Tech to emphasize their own particle physics program, they have concluded that they do not wish to add any additional adjunct faculty. Thus, Isenhower will be unable to co-chair a student's graduate committee and Sadler's adjunct appointment will expire in a year or so with no guarantee of renewal. It has been decided by the principal investigators that it would be in the best interest of ourselves and the prospective students to move this program to the University of Texas at Austin. Negotiations in 1993 with Peter Riley (Chairman) and Tom Griffy (graduate student advisor) at U.T. resulted in an informal arrangement similar to what they already have with other institutions. The students will take all coursework at U.T. and will be required to meet all of the requirements placed on any other U.T. physics graduate student. Either Sadler and Isenhower will be able to co-chair the students' committee. The advantages of working at U.T. will be that the students will have more course offerings in nuclear physics, and an expanded exposure to physics possible at the larger program there. It should be noted that there are three nuclear physics programs already in place at U.T. and the involvement of students there may lead to useful future collaborations.

The way this involvement will work will be that students who are interested in working under ACU direction will have to get accepted at U.T. Before they reach the level of Ph.D candidacy, they will be expected to obtain support via teaching assistantships (these awards will be decided by U.T., so the students must meet their acceptance criteria) during the academic year and then participate with ACU on research projects during the summers. Once they become full candidates for the Ph.D, they will move to full-time support for research on an ACU experiment.

Specifically, for the coming years Rusty Towell will be supported for increasing periods of time. Eight months of support is anticipated during this renewal period. If Towell meets U.T.'s criteria for candidacy for the Ph.D degree, he will be supported full time until the completion of his degree.

The involvement of graduate students will aid in timely analysis of data and will permit ACU to have a more continual contact with its experimental programs at the various national laboratories. Such involvement will be very important for work at FNAL and Brookhaven since they are more remote from Abilene and the experiments typically run for longer periods of time than our LAMPF experiments. The graduate students will offer more continuity in our research program and will help supervise undergraduates during the summer months.

One source of students for this program will be graduates from ACU. These students will already be familiar with our program and be able to move into an active role immediately in an experiment. By taking coursework at U.T., they will be further exposed to nuclear and particle physics. The students will be exposed to other research programs in other groups. The investigators feel that this program is superior to a small on-site graduate program at ACU. We have the resources for excellent quality Ph.D-level research projects, but cannot offer the diversity of a high quality graduate program.

VII. Publications

Submissions and publications in refereed journals, papers presented at professional meetings, and seminar presentations during 1994 are listed below.

Articles in Refereed Journals:

Performance of a Sampling Grid Scintillator, J. D. Bowman, D. Fitzgerald, M. J. Leitch, J. Ouyang, S. Hoibraten, R. J. Peterson, D. L. Prout and M. E. Sadler, Nuclear Instruments and Methods **A349**, 32 (1994).

Search for the Decay $D^0 \to \mu^+\mu^-$, By E789 Collaboration (C.S. Mishra, C.N. Brown, W.E. Cooper, H.D. Glass, K.N. Gounder, D. M. Kaplan,V. M. Martin, R. S. Preston, J. Sa, V. Tanikella, L. D. Isenhower, M. E. Sadler, L. M. Lederman, M. H. Schub, G. Gidal, M. S. Kowitt, K. B. Luk, T. A. Carey, R. E. Jeppeson, J. S. Kapustinsky, D. W. Lane, M. J. Leitch, J. W. Lillberg, P. L. McGaughey, J. M. Moss, J. C. Peng, R. Childers, C. W. Darden and P. K. Teng), Phys.Rev. **D50**, 9-12(1994).

Nuclear Dependence of Neutral D Meson Production by 800-GeV/c Protons, By E789 Collaboration (M.J. Leitch, et al.,J. Boissevain, T. A. Carey, D. M. Jansen, R. G. Jeppesen, J. S. Kapustinsky, D. W. Lane, J. W. Lillberg, P. L. McGaughey, J. M. Moss, J. C. Peng, L. D. Isenhower, M. E. Sadler, R. Schnathorst, G. Gidal, P. M. Ho, M. S. Kowitt, K. B. Luk, D. Pripstein, L. M. Lederman, M. H. Schub, C. N. Brown, W. E. Cooper,H. D. Glass,K. N. Gounder,C. S. Mishra, D. M. Kaplan,W. R. Luebke,V. M. Martin,R. S. Preston, J. Sa, V. Tanikella, R. Childers, C. W. Darden, J. R. Wilson, Y. C. Chen, G. C. Kiang, and P. K. Teng), Phys.Rev.Lett.**72**, 2542-2545 (1994).

A Fast Ring-Imaging Cherenkov Counter for a Fixed-Target Heavy-Quark Experiment, D.M. Kaplan, L.D. Isenhower, M.Atac, C.N. Brown, C.W. Darden, NIM **A343**, 316 (1994).

The Forward Ring Imaging Cerenkov Detector of DELPHI, By W. Adam et al.,(collaboration of CERN, Rio de Janeiro U., Democritos Nuclear Research Center, Genoa U., INFN at Genoa, Grenoble U., Karlsruhe U. IEKP, Cracow INP-Exp, Stefan Inst. at Ljubljana, Bohr Inst., NIKHEF, Cantabria U. at Santander, Uppsala U., Wuppertal U.), Nucl.Instrum.Meth. **A338**, 284-309 (1994).

Production of J/ψ at Large x_F in 800 GeV/c p-Copper and p-Beryllium Collisions, M.S. Kowitt et al.,G. Gidal, P. M. Ho, K. B. Luk, D. Pripstein, L.D. Isenhower, M.E. Sadler, R. Schnathorst, R. Schwindt, L.M. Lederman, M.H. Schub, C.N. Brown, W.E. Cooper, H.D. Glass, K.N. Gounder, C.S. Mishra, J. Boissevain, T.A. Carey, D.M. Jansen, R.G. Jeppesen, J.S. Kapustinsky, D.W. Lane, M.J. Leitch, J.W. Lillberg, P.L. McGaughey, J.M. Moss, J.C. Peng, D.M. Kaplan, W.R. Luebke, V.M. Martin, R.S. Preston, J. Sa, V. Tanikella, R.L. Childers, C.W. Darden, J.R. Wilson, G.C. Kiang, P.K. Teng, Y.C. Chen Phys. Rev. Lett. **72**, 318 (1994).

Elastic Scattering of Pions from ^3H and ^3He in the Backward Hemisphere, S. K. Matthews, W. J. Briscoe, C. Bennhold, B. L. Berman, R. W. caress, K. S. Dhuga, S. N. Dragic, S. S. Kamalov, N. J. Nicholas, L. Tiator, S. J. Greene, D. B. Barlow, B. M. K. Nefkens, C. Pillai, J. W. Price, L. D. Isenhower, M. E. Sadler, I. Supek and I. Slaus, submitted to Phys. Rev. C.

Inelastic Pion Scattering from ^3H and ^3He, B. L. Berman, G. C. Anderson, W. J. Briscoe, A. Mokhtari, A. M. Petrov, M. E. Sadler, D. B. Barlow, B. M. K. Nefkens and C. Pillai, submitted to Phys. Rev. C.

Contributions to Topical Conferences:

Pion-Nucleon Experimental Program at LAMPF (Recent Results and Future Experiments), M. E. Sadler, Proc. of Symposium on Mesons and Nuclei at Intermediate Energy, Dubna, Russia, 3-7 May 1994.

The Need for Improved Pion-Nucleon Data in the Overlapping Resonance Region, M. E. Sadler, Workshop on Meson-Baryon Systems, Dubna Russia, 29-30 April 1994.

Absolute Cross Sections for the $\pi^- p \rightarrow \pi^0 n$ Reaction from γ–γ Coincidence Measurements, M. E. Sadler, Thirteenth International Conference on the Application of Accelerators in Research and Industry, Denton, TX 7-10 November 1994.

A Fast Ring-Imaging Cherenkov Counter Using Visible Light Photon Counters (VLPCs), Donald Isenhower, presented at the CHARM2000 Workshop on The Future of High-Sensitivity Charm Experiments, Fermilab, June 7-9 1994, p. 198, FERMILAB -Conf-94/190.

Report by the Charmed Mesons Working Group, Donald Isenhower et al., at the CHARM2000 Workshop on The Future of High-Sensitivity Charm Experiments, Fermilab, June 7-9 1994, pp. 435-440, FERMILAB -Conf-94/190.

Proposed Measurement of π-p Elastic Cross Sections from 5-70 MeV Using a Laser Streamer Chamber, L. Donald Isenhower, at the "Large Experiments at Low Energy Hadron Machines" workshop held at the Paul Scherrer Institute, Villigen, Switzerland, April 12-15, 1994.

Papers at professional meetings (presented by first author):

Detecting Neutral-Particle Final States in Pion-Nucleon Reactions, M. E. Sadler, Texas Section of the American Physical Society, Austin, 13-15 October 1994.

$\pi^- p \rightarrow \pi^0 n$ Cross Sections in the Region of the Δ (1232) Resonance, L. Nguyen-Tansill, H. Crannell, S. Matthews, D. Isenhower, J. Redmon, M. Sadler, C. Mertz, C. Gaulard, J. Comfort, J. Wise, W. Briscoe, J. Connelly, W. Dodge, J. Amann, R. Boudrie, J. Knudson, C. Morris, M. Rawool-Sullivan, M. Whitton, B. Park, Q. Zhao, P. P. Hui, D. Smith, A. Marusic, I. Supek, N. Kozlenko and S. Kruglov, Bull. Am. Phys. Soc. **39**, 1145 (1994).

A qVt-to-PC Interface, M. E. Sadler and G. Williams, Texas Section of the APS, AAPT and SPS, Richardson, 11-12 March 1994, Bull. Am. Phys. Soc. **39**, 1320 (1994).

Data analysis for the Measurement of the Differential Cross Sections for $\pi^- p \rightarrow \pi^0 n$ and $\pi^- p \rightarrow \eta n$ at the Petersburg Nuclear Physics Institute, T. Moriwaki, L. D. Isenhower, M. E. Sadler, M. Clajus, B. Nefkens, J. Price, D. White, V. Bekrenev, N. Kozlenko, S. Kruglov, I. Lopatin and A. Mayorov, Texas Section of the APS, AAPT and SPS, Richardson, 11-12 March 1994, Bull. Am. Phys. Soc. **39**, 1324 (1994).

Pion-Nucleon Charge Exchange Scattering at Energies Near 10, 20 and 40 MeV, J. A. Redmon, B. M. Brooks, M. E. Sadler, L. D. Isenhower, and D. H. Fitzgerald, Texas Section of the APS, AAPT and SPS, Richardson, 11-12 March 1994, Bull. Am. Phys. Soc. **39**, 1324 (1994).

Monte- Carlo Simulation of Missing-Mass Experiments with the CLAS at CEBAF, A. Rose, M. E. Sadler, L. D. Isenhower and K. Beard, Texas Section of the APS, AAPT and SPS, Richardson, 11-12 March 1994, Bull. Am. Phys. Soc. **39**, 1324 (1994).

Seminars:

Student Participation in the ACU Particle Physics Research Program, L. Donald Isenhower, Workshop on Teaching Nuclear, Atomic and Surface Physics with Accelerators, University of North Texas, Denton, 5 November 1994.

Cooperative Research between ACU and the Petersburg Nuclear Physics Institute, M. E. Sadler, Faculty Scholars Lecture at Abilene Christian University, 7 December 1994.

Pion-Nucleon Scattering Around the World, M. E. Sadler, at the University of Virginia, Physics Department Colloquium, 23 February 1994.