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**MEASUREMENTS OF OBSERVABLES IN THE PION-NUCLEON
SYSTEM, NUCLEAR A-DEPENDENCE OF HEAVY QUARK
PRODUCTION AND RARE DECAYS OF D AND B MESONS**

Final

Progress Report

15 February, 1993 - 30 December, 1993

Michael E. Sadler and L. Donald Isenhower

Abilene Christian University

Abilene, TX 79699

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I. Introduction

This report summarizes the progress by the ACU particle physics research group under grant number DE-FG05-88ER40451 from the U. S. Department of Energy. The period covered is from the date of renewal (15 May 1991) to 20 December 1993 with emphasis on the progress since the last report on 15 February 1993. Laboratories where experiments (or their preparation) have been conducted during this period are the Clinton P. Anderson Meson Physics Facility at Los Alamos (LAMPF), Fermilab, the Petersburg Nuclear Physics Institute (PNPI), the Brookhaven AGS and CEBAF.

Highlights of the accomplishments and developments in this program since renewal in 1990 include (items marked with a * appear in previous reports and are not repeated in this report):

- The final paper was published for LAMPF Experiment 806, measurement of the spin rotation parameters A and R in πN scattering from 427 to 657 MeV/c. These data finish the program to obtain the first complete sets of measurements for the πN system in any momentum interval. The attainment of this goal culminates a program that was started in 1978, when the cross sections for elastic scattering, $\pi^\pm p \rightarrow \pi^\pm p$, were measured. The measurement of A and R for both of these reactions adds four observables to the six already obtained, bringing the total to ten.
- *The final paper for Experiment 804, entitled *Measurement of the Left-Right Asymmetry in $\pi^- p \rightarrow \gamma n$ from 301 to 625 MeV/c at the Backward Angles*, was published in Phys. Rev. D.
- *LAMPF Experiment 1129, publication of final results (Phys. Rev. **C44**, 2869(1991)). This experiment was a search for neutral pions from the spontaneous fission of ^{252}Cf (J. Knudson, Los Alamos, spokesperson). The collaboration included scientists from LANL and ACU. The π^0 spectrometer was set up in the P³ channel to detect low-energy pions from a 5.8 mCi ^{252}Cf source for 893 hours (source in) and 354 hours (source out) in the late summer and fall of 1988 after Exp. 849. The only beam time required for the measurement was a short run in which a 160 MeV π^- beam was stopped in a 2.5 cm polyethylene target after passing through a 60 cm graphite degrader. Detection of the low-energy neutral pions from $\pi^- p \rightarrow \pi^0 n$ confirmed that the π^0 spectrometer was operating properly. An upper limit of 1.4×10^{-11} was obtained for the branching ratio of π^0 's produced at rest.
- *Publication of a work, *Comment on "Determination of the πNN Coupling Constant from Elastic Pion-Nucleon Scattering Data"*, Phys. Rev. Lett., **68**, 548 (1992). This paper was a product of a month-long (August, 1990) visit to ACU

by two eastern European physicists, J. Stahov from Tuzla, Yugoslavia, and V. Abaev from St. Petersburg. A collaborative effort toward a new partial wave analysis of the existing πN data is continuing despite the political uncertainties in both of those countries.

- The Neutral Meson Spectrometer (NMS) at Los Alamos was implemented, culminating an involvement over three years by ACU faculty and students with LAMPF and other universities.
- Successful runs using the NMS for LAMPF Exp. 1268, $\pi p \rightarrow \pi^0 n$ Cross Sections in the Region of the Δ Resonance (M. Sadler, spokesperson) were completed in 1992 and 1993. This experiment was the first to use the NMS in the normal two-arm coincidence mode and BGO converters.
- 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.
- Another graduate student, Jimmy Redmon (former ACU undergraduate) has been added to this effort under a cooperative agreement with Texas Tech University. In this agreement, Sadler has been appointed an adjunct member of the graduate faculty at Texas Tech in order to supervise graduate theses. Meade Brooks completed his Master's thesis under this arrangement in 1991 on LAMPF Experiment 882, measurement of differential cross sections for $\pi p \rightarrow \pi^0 n$ at 10, 20 and 40 MeV near 0° and 180° , with Sadler serving as advisor.
- Fermilab Experiment 789, completion of data collection in January, 1992. This experiment has a primary emphasis on the measurements of the two-prong decays of B and D mesons (J.C. Peng, LANL and D.H. Kaplan, NIU, spokespersons). Data analysis on Fermilab Experiment 789 has continued at LANL, FNAL, and Berkeley with excellent progress. E789 has shown that it is possible to record B^0 meson events with a fixed-target apparatus. Also, this experiment has successfully measured the nuclear dependence of the production of charm quarks and a paper has been submitted for publication. E789 will also set the world's best upper limits of D^0 to dilepton decays. A paper on the $\mu^+\mu^-$ mode is now in the final draft stage and should be submitted for publication in early 1994. M. Kowitt of U.C. at Berkeley has completed his Ph.D thesis analyzing J/ψ production at large Feynman x for the possibility of an intrinsic charm component in the proton and a paper has been submitted to Phys. Rev. Letters. These results are elaborated on in Section III of this report.

- Approval of Fermilab Experiment 866 to 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 (proposal is attached as an appendix in the renewal application).
- The collaboration between Petersburg Nuclear Physics Institute (PNPI), UCLA and ACU to measure cross sections for $\pi^-p \rightarrow \eta n$ and $\pi^-p \rightarrow \pi^0 n$ near the η threshold has continued. In July 1991, the production of the η meson from the reaction $\pi^-p \rightarrow \eta n$ was identified for the first time at the PNPI laboratory during a two-week tune-up run. The results were analyzed at ACU as a mechanism to measure the central beam momentum and momentum bite ($\Delta P/P$) of the PNPI pion beam, an important facet of the measurement of $\pi^-p \rightarrow \pi^0 n$ near the η threshold. The first data runs were conducted during July and December, 1992. ACU provided essential electronics (made possible through this grant) and participated in the two measurements at PNPI in which distinct peaks for neutron time-of-flight from $\pi^-p \rightarrow \pi^0 n$ and $\pi^-p \rightarrow \eta n$ were observed. Scientists from PNPI were brought to the U.S. to work cooperatively on the data analysis and to participate in the NMS and Brookhaven program, discussed below.
- ACU undergraduate students have continued to make valuable contributions to this research effort, particularly in preparing for the PNPI and NMS experiments and in the analysis of the data. In the past three years, students worked on projects such as tomography and crystal testing for the NMS, participation in the data-taking on E1268 and at PNPI, developing software to read and translate the data tapes written on the Russian computers, and a hardware computer interface that communicates between a qVt multichannel analyzer and a microcomputer.

II. Pion-Nucleon Program

A. Complete Sets of Measurements at $P_{\text{lab}} = 427$ to 687 MeV/c

Abilene Christian University has been involved in pion-nucleon (πN) scattering experiments at the Clinton P. Anderson Meson Physics Facility at Los Alamos (LAMPF) since 1979. The experiments were conducted in collaboration with UCLA, George Washington University, Los Alamos, Catholic University and Rudjer Boskovic Institute (RBI). A tabulation of the measurements is given in Table 1. The final publications for these experiments can be found in Ref. [1-7].

The goal from the outset of this program was to obtain the first complete set of measurements ever in the fundamental πN system. This goal has been accomplished. The experimental phase in the momentum region from 378 to 687 MeV/c has come to a close. The final paper [7] was published earlier this year, marking the end of an era for this research effort.

πN interactions are described by only four scattering amplitudes (eight real numbers), assuming isospin invariance. These independent amplitudes arise from the two possible spin amplitudes (historically called spin-flip and non-spin-flip for the spin-1/2 system) and two isospin combinations ($I=1/2, 3/2$). Since an overall phase is unobservable, a minimum of seven independent measurements are needed to determine fully the scattering amplitudes. Ref. [8] shows how to obtain an unambiguous determination of the πN scattering amplitudes from the three differential cross sections, three polarization asymmetries and two spin rotation parameters. Different measurements must necessarily be at the same energies and angles.

Ten measurements were completed at selected energies and angles: $d\sigma/d\Omega$ and A_N for all three reactions, and A and R for $\pi^\pm p \rightarrow \pi^\pm p$. Plots of the measured angular distributions for these observables at 625 MeV/c are shown in Fig. 1-2. These data are now the world standard as the only complete data set in any hadronic system. Completeness is defined as enough observables to determine fully the spin and isospin amplitudes, assuming isospin invariance. The ten measurements are not completely independent, since at any given momentum and angle $P^2 + A^2 + R^2 = 1$ for any of the reactions. The data for A and R for both $\pi^+ p \rightarrow \pi^+ p$ and $\pi^- p \rightarrow \pi^- p$ provide a direct test of isospin invariance through the isospin triangles (discussed in detail in the 1990 progress report).

This program was only possible at LAMPF because of the high intensity of pion beams (particularly important for the spin-rotation measurements), the availability of both transversely and longitudinally polarized proton targets, and the JANUS polarimeter. The support of the LAMPF management over the years (spanning three different directors) was also instrumental in the success of the effort.

Contributions by ACU to this effort include participation in the design and setup of the equipment (most of which was constructed either at LAMPF or UCLA) for all of the experiments. ACU faculty and students have participated in the data-taking phase of all of the measurements. All of the actual data replay for Exp. 363 [1] and most of

the replay and analysis for Exp. 806 [7] were done at ACU. I. Supek (presently at Rudjer Boskovic Institute) spent most of his two years in Abilene working on the latter while completing his Ph.D. thesis from RBI.

Table 1. Summary of LAMPF π N Experiments

Date	Experiment	Measurement (momenta)reference
1978-79	LAMPF Exp. 363	$\frac{d\sigma}{d\Omega}$ for $\pi^\pm p \rightarrow \pi^\pm p$ (378-687 MeV/c) [1]
1979-80	LAMPF Exp. 120	$\frac{d\sigma}{d\Omega}$ for $\pi^- p \rightarrow \pi^0 n$ (300-687 MeV/c) [2]
1982	LAMPF Exp. 120*	A_N for $\pi^\pm p \rightarrow \pi^\pm p$ (471-687 MeV/c) [3]
1983	LAMPF Exp. 120**	A_N for $\pi^- p \rightarrow \pi^0 n$ (471-687 MeV/c) [4]
1984	LAMPF Exp. 804	A_N for $\pi^- p \rightarrow \gamma n$ and $\pi^- p \rightarrow \pi^0 n$ (300-625 MeV/c)[5]
1985	LAMPF Exp. 807	P for $\pi^\pm p \rightarrow \pi^\pm p$ (547-625 MeV/c) [6]
1986	LAMPF Exp. 806	A and R (spin rotation parameters) for $\pi^\pm p \rightarrow \pi^\pm p$ (427, 471, 547 and 625 MeV/c) [7]

625 MeV/c $\pi^+p \rightarrow \pi^+p$

625 MeV/c $\pi^-p \rightarrow \pi^-p$

Figure 1. Angular distributions of the eight observables measured for $\pi^\pm p \rightarrow \pi^\pm p$.

Figure 2. Angular distributions $d\sigma/d\Omega$ (top) and A_N (bottom) for $\pi^-p \rightarrow \pi^0 n$.

B. Measurements of $\pi^-p \rightarrow \pi^0n$ Using the LAMPF π^0 Spectrometer

The measurements (of both $d\sigma/d\Omega$ [2] and P [4,5] for $\pi^-p \rightarrow \pi^0n$ mentioned in the previous section were accomplished with neutron detectors in coincidence with a single photon from $\pi^0 \rightarrow 2\gamma$ decay. ACU has been active in two measurements of absolute differential cross sections of $\pi^-p \rightarrow \pi^0n$ using the LAMPF π^0 Spectrometer. These experiments (LAMPF Experiments 849 and 882) have been in collaboration with scientists from LAMPF Groups MP-4, MP-5 and MP-7 and George Washington University (GWU).

Experiment 849 (Sadler, spokesperson) was a measurement of differential cross sections for $\pi^-p \rightarrow \pi^0n$ near 0° and 180° at $P_\pi = 427, 471, 509, 547, 586, 625, 657$ and 687 MeV/c in the P^3 beam channel at LAMPF. GWU assumed responsibility for the data analysis and a M.S. thesis by Nancy Jo Nicholas on the experiment has been completed [9].

LAMPF Experiment 882 (D. H. Fitzgerald, spokesperson) was a measurement of the differential cross sections for $\pi^-p \rightarrow \pi^0n$ at $0^\circ, 90^\circ$ and 180° at $T_\pi=10, 20,$ and 40 MeV in the LEP channel. A M.S. thesis [10] by Meade Brooks on the analysis at 0° and 180° has been completed, for which Sadler served as advisor as an adjunct professor at Texas Tech University (TTU).

The special problems associated with obtaining absolute cross sections from a measurement of the $\pi^0 \rightarrow 2\gamma$ decay can be seen by investigating the formula from which the results are obtained:

$$\frac{d\sigma}{d\Omega} = \frac{Y J}{N(\pi^-) N_H \Omega(\pi^0) \varepsilon(\pi^0) \varepsilon_W f_{abs} F_{\gamma\gamma} \tau_L} \quad (1)$$

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, $\Omega(\pi^0)$ is the laboratory solid angle acceptance of the spectrometer for the two γ rays, $\varepsilon(\pi^0)$ is the π^0 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 $\pi^0 \rightarrow \gamma\gamma$ branching ratio (0.98802) and τ_L is the experimental livetime. The quantities in this equation that are peculiar to detecting neutral mesons are $\Omega(\pi^0)$, $\varepsilon(\pi^0)$, ε_W and f_{abs} . Everything else is determined by standard techniques. The statistical uncertainties in the yields are usually negligible (exceptions being the cross section measurements at very low energies in E882). Beam normalizations with uncertainties of a few percent have been obtained in other LAMPF experiments, e.g. Ref. [1]. Hydrogen target lengths can be determined to 1% if proper care is taken [1]. Uncertainties in the livetime can be kept small by limiting the beam so that $\tau_L > 90\%$.

$\Omega(\pi^0)$ must be obtained from a Monte-Carlo calculation which incorporates the geometry of the beam, target and spectrometer. A consistency check can be made using different cuts on energy sharing between the two arms, called the X parameter where

$$X = (E_1 - E_2)/(E_1 + E_2), \quad (2)$$

and E_1, E_2 are the measured energies in the two arms. Another consistency check is obtained by defining different fiducial areas in the wire chambers which follow the converters to detect the shower. In E849 and E882, four different sets of cuts (corresponding to $|X| \leq 0.2$ and $|X| \leq 1.0$ and two different fiducial areas in the wire chambers) have been used both in the replay and in the calculation of $\Omega(\pi^0)$. Consistent results are obtained in the E882 analysis, but not for E849. The program used for determining $\Omega(\pi^0)$, PIANG, is a purely geometrical calculation. Greater accuracy would be achieved if the physics of the shower propagation in the converters and wire chambers were included. The investigators have obtained software used by Emil Frlez in his dissertation thesis [11] that uses GEANT to model the spectrometer and plan on using this to help make more reliable cross section calculations.

The overall π^0 detection efficiency, $\varepsilon(\pi^0)$, for the P10 spectrometer is given by the expression

$$\varepsilon(\pi^0) = [1 - (1 - \varepsilon_c)^3]^2, \quad (3)$$

where ε_c is the efficiency for a single converter to produce a detectable charged particle. The cubic power in this equation follows from the three conversion planes per arm for the P10 spectrometer. ε_c depends on the gamma energy. A measurement using tagged γ 's of 121 MeV (obtained by measuring $\pi^- p \rightarrow \pi^0 n$ at $T_\pi = 100$ MeV, using one arm of the spectrometer as a tagger and detecting the conjugate photon with a modified arm with all but one converter plane removed) gave $\varepsilon_c = 0.286 \pm 0.002$. The energy dependence for ε_c has been obtained from modelling of the electron-gamma showers using the Stanford EGS code. The modelling took into account such effects as a conversion taking place but producing no charged particles in the region behind the converter (particularly significant for low γ energies) and occurrences of charged particles exiting backward into veto scintillators. The quantity f_{abs} , like $\varepsilon(\pi^0)$, has also been calculated using the EGS shower code.

Another advantage that is derived from detecting the $\pi^0 \rightarrow \gamma\gamma$ decay is that a large angular interval is accepted for a given position of the spectrometer. For the γ pairs accepted by a given geometry, the scattering angle is reconstructed from

$$\cos \theta_{\pi^0}^L = \frac{E_1 \cos \theta_1 + E_2 \cos \theta_2}{(E_1^2 + E_2^2 + 2E_1 E_2 \cos \eta)^{1/2}} \quad (4)$$

where $\theta_{\pi^0}^L$ is the laboratory angle of the scattered π^0 , E_1, θ_1 (E_2, θ_2) are the laboratory energy and angle, respectively, for the first (second) gamma ray and η is the opening angle between the gamma rays.

1. LAMPF Exp. 849 - Measurements of $\pi p \rightarrow \pi^0 n$ at Forward and Backward Angles at 427 - 687 MeV/c

The determination of $\theta_{\pi^0}^L$ requires uniform energy calibration of the lead-glass blocks in the calorimeter. It is this calibration that is suspect in the inconsistency of the E849 results with different X-cuts and fiducials. An example is shown in Fig. 3 (the forward-angle cross sections for $\pi p \rightarrow \pi^0 n$ at 509 MeV/c, taken from Ref. [9]). Here, the angular region $0^\circ < \theta_{cm} < 40^\circ$ was covered with three geometries for the spectrometer. The three points marked with an 'x' are the unbinned results (bin 4 included all of the acceptance), while the diamonds are the results obtained from dividing the data into multiple bins of $\theta_{\pi^0}^L$ according to Eqn. (4). Only the statistical errors are shown. The binned results show a dramatic dependence on scattering angle, which the Legendre fit is incapable of reproducing. Comparisons to the VPI partial-wave analysis [12] and to the most forward point of Borcharding [2] are also shown.

The assignment of this inconsistency to the energy calibration is further substantiated by an observed asymmetry in the energy sharing in the two arms of the spectrometer. An example from the E849 analysis is shown in Fig. 4. The vector plot shows the summed-energy histogram for the J arm of the spectrometer and the bar plot is the same for the K arm. These distributions should be the same since the arms were placed symmetrically around 0° . The difference is noticeable, but not tremendous, but does affect the angle binning using Eqn. (4).

These data are an important complement to those of Ref. [2] and were taken at the same beam momenta. The 2γ coincidence technique allows the measurement of $\pi p \rightarrow \pi^0 n$ at extreme forward and backward scattering angles. These angles are not accessible by neutron-counter techniques because of the interference of the beam for backward π^0 angles and the low energy of the neutrons for the forward π^0 angles. In addition, the detection efficiency of neutron counters is at least as difficult to determine as the acceptance-efficiency product of a 2γ spectrometer (the main source of the error bar for the square in Fig. 3). Finally, use of neutron counters necessitates a subtraction for radiative exchange, $\pi p \rightarrow \gamma n$ (inverse photoproduction). This process competes favorably with the charge exchange cross section when the latter is low because of destructive interference between different partial waves, such as the back angles near 547 MeV/c.

The investigators feel that the time has come to take over the analysis of E849 and see it through to final publication. The thesis results of Ref. [9] are not deemed publishable until the issues addressed above are resolved and no one is presently working actively on the analysis. This project can involve undergraduates, but a graduate student is needed who can be involved with the analysis over a longer period. Such a task would be an excellent "tune-up" for a student preparing for an experiment with the NMS or at BNL, described below, since the detection mechanism is the same. What is needed is the means to involve a graduate student under the direction of ACU, possibilities of which are discussed in the application for renewal.

509 MeV/c $\pi^- p \rightarrow \pi^0 n$

Figure 3

Figure 4

2. LAMPF Exp. 882 - Measurements of $\pi^+p \rightarrow \pi^0n$ at 10, 20 and 40 MeV

The bulk of the analysis of the data at 0° and 180° for E882, measurements of $\pi^+p \rightarrow \pi^0n$ at 10, 20 and 40 MeV, has been completed [10] for some time; however, publication of these data have 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 model. Recently, 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.

The analysis of the 90° data is pending but is near completion. Jimmy Redmon, a former ACU undergraduate, is presently enrolled in the graduate program at TTU and has accepted the E882 90° analysis as the problem for his Master's thesis. Redmon worked with Brooks on many aspects of the 0° and 180° analysis and started working on the 90° analysis last summer. Presently, he has an appointment as a teaching assistant and is taking courses at TTU but the investigators hope to support him again this summer under the renewal. Redmon has also participated in the NMS and PNPI efforts discussed below.

The determination of the differential cross section is dependent on three primary parameters from Eqn. (1): the yield, the lab solid angle, and the π^0 detection efficiency. The yield, or the number of π^0 's produced, is determined from the π^0 energy histograms which contain the sum of the number of π^0 '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^0 's. In addition, the wrong spacer length was inadvertently used for one of the arms, giving an asymmetric geometry which has to be modelled correctly in PIANG to calculate $\Omega(\pi^0)$ in Eqn. (1). At one time the decision was made first to publish the results for 0° and 180° , with the results for 90° to follow. Due to considerations discussed below, it was decided to make the results available to the πN community (partial-wave analysts and efforts involved in determining the πN sigma term), but to postpone publication until the 90° analysis was completed.

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^0 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 [11]. However, it is desired to do some modelling of our processes with GEANT and we have recently obtained the software used in Ref [11] 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^0 spectrometer normalize to the "known" $\pi p \rightarrow \pi^0 n$ 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 5-6. 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 7-9 for approximate energies of 10, 20, and 40 MeV, respectively. 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 [12], Karlsruhe-Helsinki [13], and the potential model of Siegel and Gibbs (their data were influenced by previously reported E882 results, so with new results their calculations may be different than shown). Also shown is a simple second order Legendre fit to the data. The reduced χ^2 is equal to 1.02, 0.25, and 11.2 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 degrees and high in the region around 90° , so the large value for the 40 MeV data is not surprising. The difference near 0° is thought to be a consequence of the analyses from Ref. [12-14] fitting a

previous measurement by our group [15], which measured forward-angle cross sections for $\pi^-p \rightarrow \pi^0 n$ 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 $\mu\text{b/sr}$, the present results overlap reasonably well with Ref. [15]. The results near 90° were only obtained in the last few weeks, and the problem there will likely be resolved in January when Redmon returns to ACU to work on the analysis again.

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 8 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. 5: Measured scattering angle (vert. bars) overlaid on PIANG distribution

Fig. 6: Measured opening angle (vert. bars) overlaid on PIANG distribution

10.5 MeV (55 MeV/c) $\pi^- p \rightarrow \pi^0 n$

Fig. 7: Differential cross sections from E882 for 10 MeV data (statistical errors only).

20.7 MeV (77 MeV/c) $\pi^- p \rightarrow \pi^0 n$

Fig. 8: Differential cross sections from E882 for 20 MeV data (statistical errors only).

39.5 MeV (112 MeV/c) $\pi^- p \rightarrow \pi^0 n$

Fig. 9: Differential cross sections from E882 for 40 MeV data (statistical errors only).

C. LAMPF Exp. 1268: $\pi p \rightarrow \pi^0 n$ Cross Sections in the Region of the Δ Resonance Using the NMS Spectrometer

The experimental phase for LAMPF Exp. 1268, $\pi p \rightarrow \pi^0 n$ Cross Sections in the Region of the Δ Resonance (M. E. Sadler, spokesperson) was completed in September, 1993. 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.

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^0 spectrometer to measure absolute cross sections for $\pi p \rightarrow \pi^0 n$ led to an active involvement in the development of the NMS at LAMPF. The NMS is based on the same principle as the π^0 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.

ACU has been active in the design and implementation of the NMS from its inception. Sadler served on the committee on the design and construction of the NMS, making regular trips to LAMPF for the meetings. There has been extensive involvement by ACU students, starting in 1990 when Scott Garner and Jason Phillips assisted in the construction of wire chambers for the NMS and the related tomography studies (described below). Keith Elmore and Tyson Browning spent the summer of 1991 at LAMPF assembling the tomography apparatus and developing software for the analysis. The activity picked up in the summer of 1992 in preparation for the test run of the spectrometer in the P^3 channel. Six ACU students (Browning, Elmore, Sam Brown, Tomohiro Moriwaki, Jimmy Redmon, Andrew Rose) and Aljosa Marusic from Rudjer Boskovic Institute were supported under a combination of funds from this grant and group MP-10 at LAMPF. Students participating in 1993 before the commissioning of the NMS (with the full support structure) and the running of Exp. 1268 were Jake Caire, Craig Collins, Sean Dodson, David Rigsby, Terry Thomas and Joshua Willis. Activities in which the students participated include 1) testing crystals and phototubes, 2) performing the tomography tests, 3) assisting in the staging of the NMS and beam monitoring apparatus in the P^3 and LEP channels, and 4) preparing for the first data acquisition with the device. Several MP-10 staff members supervised the students at different stages during their summer involvements. This arrangement worked out well for both efforts in that increased summer research opportunities were made available to the students and they, in turn, made meaningful contributions to the NMS effort.

The CsI crystals and phototubes for the NMS were first tested individually for adequate fast/total light output. Enough had arrived by summer of 1992 to start a developmental program with the first arm of the device. After the full 10x6 array was

tested with cosmic rays and with beam in the P³ channel, ACU participated in Exp. 1272, *Pion Single Charge Exchange on the Deuteron (π -d $\rightarrow$ π nnn): A Tune-up Experiment for the Neutral Meson Spectrometer*, J. L. Matthews (Massachusetts Institute of Technology), and M. Whitton (Los Alamos National Laboratory), spokespersons. This experiment utilized a single arm of the NMS (with no converter planes) located very close to the target so that both of the decay γ 's were intercepted. These data are presently being analyzed by Hojoon Park at MIT as part of his Ph.D. thesis.

Experiment 1268 received beam for a test run late in 1992. Delays in the delivery of the remaining CsI crystals and phototubes for the second arm caused the experiment to be delayed until the last beam cycle. A ten-day tune-up run was completed in October, 1992, in which the cross sections were measured near 0° at six momenta (241, 272, 299, 326, 350 and 378 MeV/c). This experiment was the first to use both arms of the NMS and the first to implement the converter planes. A temporary support structure was used which positioned the arms symmetrically around the beam axis.

Preliminary cross sections from the 1992 run (an excitation function at 0°) are shown in Fig. 10. The results shown are for wide-open fiducials only. Differences for values of energy sharing ($XCUT \leq 0.2$ and $XCUT \leq 1.0$ were used) are 20% in some cases. This difference is expected to disappear as the energy calibration and solid angles are better determined. The replay program needs to be modified to analyze the data for a restricted fiducial area of the spectrometer arms in order to check the geometry of both the analysis and the solid-angle determination. Development of this task is discussed in the renewal.

The data acquisition phase for this experiment was completed in September 1993. The full support structure was finished in the interim and a second converter plane was added to each arm of the NMS. Data were taken over the full angular range, including 180°. A full list of energies and geometries is given in Table 1. The angular acceptance of the NMS is nearly 40°, so the measurements at 47.5° and 108° provide important overlap points to measure the same cross section with different geometries. Data at the same lab angle were sometimes taken with the opening angle of the NMS arms at different values, also for a consistency check. The following contribution to the Vth International Symposium on Meson-Nucleon Interactions, held in Boulder, CO on 6-10 September of this year, summarizes the status of the experiment to date.

This analysis of this experiment is being done by Linh Nguyen-Tansill of Catholic University as part of her Ph.D. thesis. She initially utilized the Microvax 3600 computer at ACU for the replay. This interaction was made possible by remote login using Internet. She has made two trips to Abilene to discuss the analysis, using travel funds from this grant. CUA has now installed the 'Q' system on their Vax computer and added a high-capacity disk drive for spooling the data, so this system is now being used for the replay of the data taken this year.

Fig. 10: Preliminary forward-angle differential cross sections from Exp. 1268

LAMPF EXPERIMENT 1268

$\pi^- p \rightarrow \pi^0 n$

SUMMARY OF ENERGIES AND ANGLES

T_π (MeV)	P_π (MeV/c)	NMS LAB ANGLES					
		100°	200°	47.50°	750°	1080°	1800°
138.8	240.9	✓	✓	✓	✓		✓
166.0	271.8	✓	✓	✓	✓		✓
190.0	298.6	✓	✓		✓	✓	✓
214.6	325.5	✓	✓	✓	✓	✓	✓
237.0	349.8	✓	✓	✓	✓	✓	✓
263.0	377.6	✓	✓		✓	✓	✓

Table 1: Summary of measurements for Exp. 1268

MEASUREMENTS OF PION-NUCLEON CHARGE EXCHANGE
NEAR THE Δ RESONANCE USING THE NMS AT LAMPF

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Abstract

A measurement of $\pi^-p \rightarrow \pi^0n$ cross sections near the Δ resonance, LAMPF Experiment 1268, is in progress. The new Neutral Meson Spectrometer at Los Alamos is used to detect the π^0 through the $\gamma\gamma$ decay mode. The goals of the experiment are: (1) to check existing data that do not agree well with partial wave analyses (PWA's) at the back angles near the Δ , (2) to provide accurate data for input to charge-dependent PWA's, (3) to investigate charge splitting of the Δ , and (4) to complement existing and future measurements of $\pi^\pm p \rightarrow \pi^\pm p$ that should help clarify the discrepancies at lower energy through analyticity constraints of the PWA's.

The LAMPF Neutral Meson Spectrometer (NMS) is shown in Figure 1. LAMPF Experiment 1268 is the first to use this detector in the two-arm coincidence mode. The present configuration of each arm is a plane of scintillators for vetoing charged particles, two converter planes and a calorimeter. Each converter plane consists of an active layer of bismuth germanate (BGO), dimensions 14" x 28" x 0.25" (thickness), followed by cathode-strip chambers to reconstruct the $\gamma \rightarrow e^+e^-$ vertex. The calorimeter consists of a 6 x 10 array of pure CsI crystals, each 4" x 4" x 12" (thickness). The thicknesses of each BGO converter and the CsI calorimeter correspond to slightly more than 0.5 and 16 radiation lengths, respectively. The final configuration will have a total of four conversion planes in each arm. The NMS is designed to provide an order-of-magnitude improvement over the π^0 Spectrometer in rate and energy resolution, and provides more than a factor of two increase in solid angle. The enhanced energy resolution of the NMS is not required for measurements of $\pi^+p \rightarrow \pi^0n$, but does aid in background rejection.

Fig. 1 The LAMPF Neutral Meson Spectrometer

The low-energy-pion (LEP) channel at LAMPF was used to provide π^- beams at kinetic energies of 138.8, 166, 190, 214.6, 237 and 263 MeV. These energies were selected to complement the measurement of elastic $\pi^\pm p \rightarrow \pi^\pm p$ cross sections at TRIUMF1. The NMS was placed at central angles in the laboratory of 20° , 75° and 180° for each of these energies. Additional measurements were made at 47.5° and 108° for some energies. The arms of the NMS were positioned to detect γ -rays from the π^0 decay out of the $\pi^- p \rightarrow \pi^0 n$ scattering plane, as approximately depicted in Fig. 1 with the π^- beam going into the figure at a height between the crates of the active elements. For the 20° and 180° measurements the beam passed between the crates, inside the support structure. The radial distance of the arms was slightly more than one meter, so that π^0 's were detected at angles of approximately $\pm 20^\circ$ from the central angle. The scattering angle of each π^0 is reconstructed in software from the determination of the direction and energy of the γ -rays.

The primary target used in the experiment was 2 cm of CH_2 . A carbon target with the same energy loss for the incident π^- was used for background subtraction. An example of the reconstructed π^0 kinetic energy at $T_\pi = 190$ MeV, $\theta_{\text{NMS}} = 20^\circ$, is shown in Fig. 2 for both of these targets. Here, the situation is quite favorable because of the difference in Q values for charge exchange scattering on protons and carbon. The width of the peak in Fig. 2 is dominated by the kinematic broadening of detecting π^0 's over the angular interval $0^\circ \leq \theta_{\text{lab}} \leq 40^\circ$.

Fig. 2. Reconstructed π^0 kinetic energy for charge-exchange scattering from CH_2 and C targets. The central NMS angle here is 20° .

The solid angle acceptance of the γ -rays from the $\pi^0 \rightarrow \gamma\gamma$ decay must be calculated from a Monte-Carlo simulation. Existing programs are being modified to incorporate precise coordinates obtained from surveys of each NMS geometry and to calculate acceptances for different bins of the lab scattering angle. This angle is calculated from

$$\cos \theta_{\text{lab}}^{\pi^0} = \frac{E_1 \cos \theta_1 + E_2 \cos \theta_2}{[E_1^2 + E_2^2 + 2E_1 E_2 \cos \eta]^{\frac{1}{2}}} \quad (1)$$

where $E_{1,2}$ are the energies of the two γ rays, $\theta_{1,2}$ are their lab angles, and η is the opening angle between them. The program must accurately model both the energy response and the vertex determination of the NMS before reliable acceptances (and hence absolute cross sections) can be obtained.

The most comprehensive existing data for $\pi p \rightarrow \pi^0 n$ cross sections near the Δ are those of Jeneffsky², et al. Neutrons were measured using TOF. These data are compared with the VPI³ and Karlsruhe-Helsinki⁴ partial wave analyses in Fig. 3 at 193 and 246 MeV. Forward-angle measurements by Bayer⁵, et al., are included for both energies and data by Hauser⁶, et al., are included at 246 MeV. The Jeneffsky data are seen to be systematically higher than the PWA's at the back angles in this energy interval at and above the Δ .

The present measurements will provide a means to check the existing data over the complete angular distribution using a totally different detection technique. Combined with the measurements of Ref. 1, new data will be available to investigate the charge splitting of the Δ .

References:

- [1] M. M. Pavan, et al., Vol. I of the proceedings of this symposium.
- [2] R. F. Jeneffsky, et al., Nucl. Phys. **A290**, 407 (1977).
- [3] R. A. Arndt, J. M. Ford and L. D. Roper, Phys. Rev. **D32**, 1085 (1985). The SM90 solution was obtained from the SAID program, available from the authors.
- [4] R. Koch and E. Pietarinen, Nucl. Phys. **A336**, 331 (1980).
G. Höhler, F. Kaiser, R. Koch and E. Pietarinen, Handbook of Pion-Nucleon Scattering, Physics Data No.12-1 (1979).
G. Höhler, Pion-Nucleon Scattering, in Landolt-Börnstein **9b**, Springer-Verlag (1982).
- [5] W. Bayer, et al., Nucl. Inst. and Meth. **134**, 449 (1976).
- [6] M. G. Hauser, et al., Phys. Lett. **35B**, 252 (1971).

302 MeV/c (193 MeV) $\pi^-p \rightarrow \pi^0 n$

359 MeV/c (246 MeV) $\pi^-p \rightarrow \pi^0 n$

Figure 3. Existing data and analyses for $\pi p \rightarrow \pi^0 n$ near the Δ resonance.

D. Measurement of the Differential Cross Sections for $\pi^-p \rightarrow \eta n$ and $\pi^-p \rightarrow \pi^0 n$ at the Petersburg Nuclear Physics Institute

1. Historical Background and Summary of Experimental Program

Physicists from the St. Petersburg (formerly Leningrad) Nuclear Physics Institute (PNPI), the University of California at Los Angeles (UCLA), and Abilene Christian University (ACU) have formed the Collaboration of United States and Soviet Union Physicists (CUSP). For the first phase, the collaboration is using the existing zero-degree pion channel at the 1 GeV proton synchrocyclotron at PNPI to measure differential cross sections for $\pi^-p \rightarrow \eta n$. The primary detectors are the existing neutron counters from UCLA. The original goal, and still one being considered, was to measure the cusp (sharp change in the cross sections as the η threshold is traversed) for $\pi^-p \rightarrow \pi^0 n$. This experiment was postponed in lieu of the measurement of η production because of the lack of electronics and the need for better gamma detectors for the charge-exchange measurement.

A short history of the CUSP collaboration is given below:

- September 1986 - Sadler made the first trip to the Soviet Union, to attend the International Conference on High Energy Spin Physics at Protvino (near Moscow). He arranged to visit the Leningrad Nuclear Physics Institute after the conference to make contact with the group involved in pion-nucleon (πN) scattering measurements. This marked the first personal contact between our group (the UCLA-GWU-ACU collaboration working at Los Alamos) and the group in Gatchina, the two major experimental efforts in the world that were involved in the study of the πN interaction. Sadler gave a seminar (in Russian) on the LAMPF program and results to date.
- September 1989 - LNPI hosted the Third International Symposium on Pion-Nucleon and Nucleon-Nucleon Physics. Ben Nefkens (UCLA) and Sergei Kruglov (LNPI) first discussed the possibility of a collaborative effort to measure observables for $\pi^-p \rightarrow \pi^0 n$ at LNPI. The primary motivation for doing the experiment at LNPI was that higher energy pion beams were available than at the meson facility (LAMPF) at Los Alamos. Of particular interest was the energy region above the opening of the η threshold (685 MeV/c), just out of reach in the pion channels at LAMPF.
- July 1990 - Ben Nefkens and Sadler went to Gatchina to formalize the collaboration. Letters of Agreement were drafted between LNPI and the American institutions. LNPI agreed to assume responsibility for the beam, the gamma detectors, and most of the electronics. UCLA agreed to provide the neutron detectors. ACU agreed to provide a multichannel analyzer and time-to-digital converters (TDC's), pending approval of funding by USDOE.
- August 1990 - Vladimir Abaev, a πN partial wave analyst with the LNPI group, spent one month in Abilene with Sadler and Jugoslav Stahov (Tuzla, Bosnia) to work on the analysis of existing πN data and discuss plans for the future.
- Fall 1990 to Spring 1991 - Vladimir Bekrenev and Igor Lopatin made visits to UCLA and ACU to test the neutron counters and to plan the experimental program.

- Summer 1991 - ACU (Sadler and two students, Scott Garner and Jason Phillips) and UCLA (Nefkens and two students, John Price and David White) participated in the setup of the experiment in Gatchina. Since enough electronics to implement the gamma detectors were not available, it was decided first to measure the production of eta (η) mesons via the process $\pi p \rightarrow \eta n$ near threshold, utilizing only the neutron counters. A feasibility run was completed, demonstrating that better discriminators and more TDC's were needed for the neutron signals. Nevertheless, η mesons were identified at PNPI for the first time.
- Summer 1992 - Donald Isenhower, two students (Scott Garner and James Redmon) and Sadler went to participate in the first production running of the experiment to measure eta production at threshold. New constant-fraction discriminators and TDC's had been provided by ACU and UCLA in the interim. The ACU electronics were made possible by the supplemental funding provided by DOE. The first data with distinct peaks showing eta production were obtained, but the experiment was forced to concentrate on background measurements when the liquid hydrogen target failed.
- December 1992 - Martin Clajus (UCLA) and Sadler returned to PNPI to participate in another run to complete the measurement of $\pi p \rightarrow \eta n$ at momenta near threshold (670, 680, 690, 700, 710 and 720 MeV/c). Three momentum scans were completed with varying experimental conditions during one week of beam time.
- Summer 1993 - Igor Lopatin visited Abilene during the month of May. Analysis activities centered on how to extract the yields for $\pi p \rightarrow \eta n$ and $\pi p \rightarrow \pi^0 n$ from the background processes $\pi p \rightarrow \pi^0 \pi^0 n$ or $\pi p \rightarrow \pi^+ \pi^- n$. Nick Kozlenko arrived in July, spending time at BNL (Exp. 890), Abilene, Los Alamos (Exp. 1268) and Los Angeles. Sergei Kruglov arrived in Abilene in August. Time in Abilene was spent comparing analysis results. Kruglov and Kozlenko accompanied Sadler to the Vth Int. Symp. on Meson-Nucleon Physics and the Structure of the Nucleon in Boulder. They each participated in the final run of Exp. 1268 in mid September before returning to Gatchina.

While there are several active collaborations between Russian and western scientists, this program is the only one known by the investigators that has utilized an accelerator facility in the former Soviet Union in recent years. The data tapes from the December 1992 run have been read at ACU and converted to NTUPLES format using the CERN HBOOK and PAW software packages. ACU is the logical place to perform this analysis, utilizing our Vax computers and Unix workstations. The mainframe computers at PNPI were marginally adequate for this task and have been decommissioned in favor of a small number of PC workstations.

2. Measurements of $\pi p \rightarrow \eta n$ and $\pi p \rightarrow \pi^0 n$ at 670-720 MeV/c

The measurements of $d\sigma/d\Omega$ for $\pi p \rightarrow \eta n$ near threshold ($P_\pi = 685.5$ MeV/c) were initially started as a means of calibrating the pion beam momentum at PNPI. There is intrinsic interest in this measurement near threshold because the cross

section is large, so by time reversal, the η interaction with the nucleon is also large. This final-state interaction will interfere with the dominantly s-wave production of the η near threshold, giving a t dependence. Binnie, et al.[16], measured the t dependence by varying the incident beam momentum. Multiple neutron counters will allow this measurement to be done by varying the angular distribution of recoil neutrons at momenta above threshold. Information on the ηN interaction can then be extracted.

Neutrons from $\pi^- p \rightarrow \pi^0 n$ and $\pi^- p \rightarrow \eta n$ can be identified by time-of-flight (TOF). The experimental geometry is shown in Fig. 11. Neutron arrays N3-N6, at lab angles up to 12° , were instrumented with American constant-fraction discriminators (CFD's) and time-to-digital converters (TDC's). The neutron counters were placed nearly 5 m from the target in order to obtain adequate timing separation. The neutron counters are 8.9 cm wide by 25.4 cm high by 25.4 cm deep. As indicated in Fig. 11, each array consists of three counters, giving a total array width of 26.7 cm. Each counter is viewed by two phototubes (up and down), so the four arrays necessitated 24 channels of CFD and TDC.

The liquid hydrogen (LH_2) target was a cylinder 10 cm in diameter. The target was surrounded by anticounters in the scattering plane (not shown in Fig. 11) to veto any charged particle final states.

The π^- beam was elliptical, 1.5 cm high by 3.5 cm wide (FWHM) with $\Delta p/p = 1.5\%$. The beam was deflected to the right by a dipole magnet (not shown in Fig. 11). Narrow beam hodoscope counters were placed in the channel at a position where the beam is momentum-dispersed in order to tag the π^- 's into two bins with $\Delta p/p \approx 0.75\%$. These counters had a large background counting rate, presumably from neutrons originating in the beam stop. This background will present a problem in extracting the beam normalization for each momentum bin, as $\approx 15\%$ of the events have a signal from both beam hodoscope counters. Resolution of this problem is one of the immediate goals in the analysis of the data.

Neutron TOF measurements to identify $\pi^- p \rightarrow \pi^0 n$ and $\pi^- p \rightarrow \eta n$ scattering were acquired at $P_\pi = 670, 680, 685, 690, 700, 710$ and 720 MeV/c. A sample TOF spectrum at 700 MeV/c is shown in Fig. 12 for counter N42, located at 2.01° . The TDC calibration is 0.1 ns/channel. The dominant peak is the prompt gamma flash from γ rays originating in the target through a variety of processes (e.g., $\pi^0 \rightarrow \gamma\gamma$). This peak defines the reference for timing. The small peak to the left of the γ flash is electronic in origin. The " π^0 peak" just to the right of the γ flash in Fig. 12 corresponds to the detection of neutrons from $\pi^- p \rightarrow \pi^0 n$. The centroids of these peaks are separated by 6.2 ns. The γ flash and the π^0 peak each have a width ≈ 2 ns (FWHM), indicating a standard deviation of $\sigma \approx 1$ ns. This timing resolution is a factor of 2-3 better than that obtained in the earlier running without the CFD's provided by ACU and UCLA.

Two characteristics of $\pi^- p \rightarrow \eta n$ near threshold are 1) the production of neutrons is confined to a forward cone in the lab and 2) a single lab angle corresponds to two different neutron angles in the cm frame. Two peaks for η production are seen in the TOF spectrum in Fig. 12, corresponding to forward and backward cm angles. These peaks, located at 16 and 29 ns to the right of the γ flash, ride on a continuum

background of neutrons from $\pi^-p \rightarrow \pi^0\pi^0n$ and $\pi^-p \rightarrow \pi^+\pi^-n$. This continuum starts just 0.7 ns to the right of the π^0 peak. The η peaks are wider due to the intrinsically larger kinematic broadening from the angular acceptance of the neutron counters.

A spectrum taken at 670 MeV/c, below η threshold, is shown in Fig. 13. The vertical scale is expanded to deemphasize the γ flash and to show the π^0 peak and $\pi\pi$ background more clearly. The solid curves in Fig. 2,3 are fits to the spectra assuming Gaussian shapes for the peaks and a background of the form

$$A\left[e^{\frac{-(x-\delta)}{\tau_1}} - e^{\frac{-(x-\delta)}{\tau_2}}\right] + B, \quad x \geq \delta$$

where x is the channel number and A , B , δ , τ_1 and τ_2 are fit parameters. A constant ($=B$) is used for $x < \delta$, where δ is the "turn on" point for the $\pi\pi$ background. This difference in two exponentials (note the different decay constants, τ_1 and τ_2) produces the shape shown as dashed curves in Fig. 2,3. This shape was inspired by a GEANT simulation of the neutron acceptance for 2π production carried out by Vladimir Abaev at PNPI. The coding of the fit procedure was done using the MINUIT minimization routine from the CERN library and was implemented by Tomohiro Moriwaki, an ACU undergraduate.

Small shifts in the TOF spectra were observed to occur during the running of the experiment. Presumably, these shifts arose from the trigger timing since all spectra were affected. These shifts degraded the quality of the data because the timing peaks became less sharp. In principle, corrections can be applied by monitoring the position of the γ flash throughout the run and adjusting accordingly. This exercise will be somewhat tedious.

The PNPI group has minimized the effect of the timing shifts in their analysis by summing all the counts in the η region as shown in by the cross-hatched area in Fig. 14. The background contribution is evaluated by summing the counts in the same region below threshold and extrapolating as a function of beam momentum using a straight line. A plot of normalized yield as a function of momentum is shown in Fig. 15, where the straight line denotes the extrapolated background. Note the reasonable smoothness of the data from the two different beam hodoscope counters, denoted by the asterisks and diamonds.

The present plan is for ACU and PNPI to determine the η yields independently using the different techniques described. Comparison of the results will help to determine the systematic error of extracting the η yield.

Figure 11. Experimental layout for measurement of $\pi^-p \rightarrow \eta n$ at PNPI.

Figure 12. TOF spectrum taken at 700 MeV/c, above η threshold. Figure 13. TOF spectrum taken at 670 MeV/c, below η threshold.

Figure 14. Sample spectrum showing the PNPI technique for extracting yields in the "η region", shown by the cross-hatched area.

Eta yield Theta N = 6.26 deg.

Figure 15. Momentum dependence of the normalized yield in the "η region" shown in previous figure. The straight line shows the extrapolated background.

3. Assessment of Future Possibilities in the CUSP Collaboration

The collaboration derived its name from the planned measurement of the cusp in the differential cross sections for the reaction $\pi^-p \rightarrow \pi^0n$ at $P_\pi = 657-717$ MeV/c. Measurements of sufficient momentum resolution and accuracy are needed to deduce the effect of the opening of the ηn channel on the charge exchange cross section. A cusp, or discontinuity in the slope of the cross section as a function of momentum (at fixed angle), is expected at the threshold (685.5 MeV/c) for η production. The experiment involves binning the pion beam at PNPI, which has a full acceptance of $\Delta p/p = 6.0\%$, into eight intervals of 0.7% using a scintillator hodoscope placed in the channel where the beam is momentum dispersed. This hodoscope was rebuilt and installed in the PNPI beam line in early 1992. As described in the previous section, the operation of this hodoscope is suspect because of the large neutron background. A decision on the continuation of this effort at PNPI will not be made until the data discussed above, complete with the momentum binning from the hodoscope, are analyzed. The experimental layout along with Monte-Carlo calculations of the acceptance for $\pi^-p \rightarrow \pi^0n$ (performed at ACU) were detailed in earlier progress reports to DOE and are not repeated here.

Depending on the success of these programs, another possible experimental program is the measurement of differential cross sections for $\pi^-p \rightarrow \pi^0n$ at $P_\pi = 400-700$ MeV/c. The PNPI group is constructing a new Csl spectrometer to measure the 2γ 's from π^0 decay. The principle is the same as for the Neutral Meson Spectrometer (NMS) at Los Alamos, except that the PNPI version will not have converter planes. Improvements over previous measurements should be possible due to the improved gamma detection (better energy resolution) and the elimination of the uncertainty in the overall normalization due to the efficiency of the neutron counters. Precise differential-cross-section data are needed to investigate charge splitting in the pion-nucleon (πN) system and to deduce the parameters (mass, width and inelasticity) of the P_{11} and S_{11} resonances. No commitment has been made by ACU at this point to participate in this program, but informal invitations have been made by both parties to further the collaboration (by PNPI to ACU to become involved in their new spectrometer and by ACU and UCLA to PNPI to participate in the program at BNL discussed below).

At this point, the investigators have concluded that participation at PNPI must receive secondary priority to the new programs at BNL, CEBAF and Fermilab discussed below and in the application for renewal. If approved at BNL, the spectra that required a week at PNPI could be obtained in a few hours of beam time at BNL. Furthermore, the anticipated use of the SLAC crystal ball at BNL will allow a measurement of the full angular distribution for $\pi^-p \rightarrow \pi^0n$ and $\pi^-p \rightarrow \eta n$ using the characteristic $\pi^0 \rightarrow \gamma\gamma$ and $\eta \rightarrow \gamma\gamma$ decays. Also a factor in this decision is the economic difficulty that PNPI is experiencing in running the synchrocyclotron. The group has had two planned runs canceled since the last run in December 1992 due to the lack of funds to pay for the power.

Finally, another aspect of the collaboration is the partial wave analysis (PWA) of πN scattering data. The PWA uses results from all of the experimental programs described. An ongoing PWA effort is needed to complement these programs, to incorporate the recent data from LAMPF (UCLA-ACU-GWU collaboration) and PNPI in this energy region, and to prepare for future πN experiments in the overlapping resonance region (see the section of this report discussing the new involvement at the Brookhaven AGS). A state-of-the-art analysis will involve a pruned database including the most reliable data, the incorporation of complete sets of data at a single momentum (including measurements of the A and R spin rotation parameters obtained at both LAMPF and PNPI), and inclusion of constraints from dispersion theory to obtain a unique solution. The partial wave analysis is largely done by V. V. Abaev at PNPI.

References for Section II:

1. M. E. Sadler, et al., Phys. Rev. **D35**, 2718 (1987).
2. F. O. Borcharding, UCLA thesis, 1982 (unpublished).
3. A. Mokhtari, et al., Phys. Rev. **D35**, 810 (1987).
4. J. A. Wightman, et al., Phys. Rev. **D36**, 3529 (1987).
5. G. J. Kim, et al., Phys. Rev. Lett. **56**, 1779 (1986), and Phys. Lett. **B219**, 62 (1989), and Phys. Rev. **D41**, 733 (1990).
6. C. J. Seftor, et al., Phys. Rev. **D39**, 2457 (1989).
7. I. Supek, et al., Phys. Rev. **D47**, 1762 (1993).
8. N. W. Dean and P. Lee, Phys. Rev. **D5**, 2741 (1972).
9. N. J. Nicholas, GWU thesis, 1990 (unpublished).
10. B. M. Brooks, Texas Tech thesis, 1992 (unpublished).
11. Emil Frlez, University of Virginia Ph.D dissertation, May 1993 (unpublished).
12. R.A. Arndt, J.M. Ford and L.D. Roper, Phys. Rev. **D32**, 1085 (1985), updated periodically in the SAID program.
13. 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).
14. P. B. Siegel and W. R. Gibbs, Phys. Rev. **C33**, 1407 (1986).
15. D. H. Fitzgerald, et al., Phys. Rev. **C34**, 619 (1986).
16. D. M. Binnie, et al., Phys. Rev. **D8**, 2789 (1973).

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

A. E789: Introduction

Abilene Christian University has been a collaborator since October, 1988 on Fermilab E789, a fixed target experiment. This collaboration consists of 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. E789 was approximately one month later in its startup than other FNAL experiments due to safety studies needed for the high rate conditions requested.

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 currently underway at FNAL, LANL, and LBL with most of the first pass analysis now completed. Analysis of large x_F data for the possibility of an intrinsic charm component in the proton has been completed and was the subject of the Ph.D thesis of M.S. Kowitt of U.C. of Berkeley [7] and a paper has been submitted to Phys. Rev. Letters [8]. A paper on the A-dependence of D meson production has been submitted to Phys. Rev. this fall. A final draft of a new world limit for the decay $D^0 \rightarrow \mu^+ \mu^-$ has been prepared and will be submitted for publication early in 1994. NIM papers will also likely be submitted on the trigger processor, silicon strip detectors, and the data acquisition system.

B. E789: 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 $B^0 \bar{B}^0$ 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 $B \rightarrow h^+ h^-$ (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. Another interesting observation is to compare the lengths of the entries in the Particle Data Group tables on the B meson in

1988 to the entries in 1992. This indicates the large amount of effort currently underway on this topic throughout the world.

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 Y (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 , $\Lambda_b \rightarrow h^+h^-$ (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 $B_d, B_s \rightarrow \mu\mu$, $e\mu$, ee ; $B \rightarrow J/\psi$, ψ' , χ_0 ; and $\eta_b, Y, \chi_b \rightarrow h^+h^-$. 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 $D \rightarrow \pi K$ 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 $B \rightarrow J/\psi X$, $\chi^0 X$, and $\psi' X$ inclusive decays,
- 10) to search for exclusive dilepton decays $B \rightarrow \mu^+\mu^-$, 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 Y 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 Y 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 Y (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^0 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^0 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 (≥ 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 Y , have easily detectable experimental signals and can be used to analyze the dynamics of reaction processes.

C. E789: Preliminary Results

Over the next year the E789 collaboration will be able to judge its success in obtaining the goals set out in Section B. Due to the delayed startup of E789 because of safety issues, over one month of running was lost. Newly imposed radiation limits in the Fermilab experimental areas also forced E789 to run at roughly one-half of the requested intensity. In spite of these problems, E789 will still be able to set the world's best upper limits of D to dilepton decays (current PDG value is 1.1×10^{-5} and E789 limit appears to be 0.72×10^{-5}). A final draft of a paper on this topic is currently being circulated around the collaboration and should be submitted for publication in early 1994. The limits for B decays into dileptons and dihadrons will not likely fare as well, with the best limits only being around 10^{-4} . Losses due to reduced running time, lower beam intensities and lower beam energies (the Tevatron only delivered 800 GeV beams instead of the hoped for 900 GeV) were responsible for roughly a factor of 5 of reduction in sensitivity. An additional loss of a factor of two came due to the trigger processor not being as efficient for B mesons as expected (this was mostly due to hardware problems). Thus, all the B decay mode yields given will be lower than proposed by roughly a factor of 10.

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 was the topic of M.S. Kowitt's thesis [7] and a paper has been submitted to Phys. Rev. Letters [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 do a quick 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 $< 2.3 \times 10^{-3}$ nb/nucleon for Cu and $< 1.3 \times 10^{-2}$ 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 horizontal 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 preliminary result for D-meson A-dependence production cross section is

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

A paper on this topic is in the final stages of preparation and should be submitted for publication before the spring of 1994.

The B analysis has concentrated on the $B \rightarrow J/\psi X \rightarrow \mu^+ \mu^- X$ data. Currently we have 17 candidates for this B decay mode, and it is expected that we will have roughly 50-100 events after all the data have been analyzed. Figure 8 shows the $\mu^+ \mu^-$ mass spectrum for ~30% of our data. Figure 9 shows the same mass spectrum for downstream and upstream events. The downstream case (top) has 17 events consistent with the hypothesis that we are indeed seeing $B \rightarrow J/\psi X \rightarrow \mu^+ \mu^- X$. Work is currently underway to improve the vertex and mass resolution by applying small corrections to the data needed due to small errors in the way tracks are swum through the magnetic fields of SM12 and SM3. Present results look very promising but are too premature to include in a report at this time.

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 has been put on hold since there are no funds to build the new detector components. The only aspect of this proposal still being worked on as a very low priority item is Isenhower's work with D. Kaplan, C. Brown, C. Darden, and M. Atac on a Ring Imaging Cherenkov (RICH) detector for particle identification with extremely high capability [14]. This device would take advantage of Visible Light Photon Counters (VLPCs) 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, LBL-34790, UC-414, Preprint, October 1993.
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.

E789 SCHEMATIC (PLAN VIEW)

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Average decay length for B-meson ($\langle p \rangle \sim 150 \text{ GeV}$)
is $\sim 1.2 \text{ cm}$

Figure 6

Figure 7

$\mu^+\mu^-$ mass spectrum

Preliminary

mass mumu 1

Mass (GeV)

Figure 8

Very Preliminary

Figure 9

IV. New Programs at the Brookhaven AGS and CEBAF

A. Charge Symmetry Measurement at the Brookhaven AGS

ACU has joined the E890 collaboration at the Brookhaven AGS, *A New Test of Charge Symmetry in Eta Production on Deuterium..* The spokespersons are B. M. K. Nefkens of UCLA, R. E. Chrien of Brookhaven and J. C. Peng of Los Alamos, involving scientists from UCLA, BNL, LANL, Jülich, Rudjer Boskovic Institute, Petersburg Nuclear Physics Institute and ACU.

The test consists of a measurement of the ratios of the doubly differential cross sections given by

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

$$R_{\pi} = \frac{d^2\sigma(\pi^+d \rightarrow pp\pi^0)}{d^2\sigma(\pi^-d \rightarrow nn\pi^0)}$$

Charge symmetry (CS) requires that both R_{η} and R_{π} equal to 1.0 for all incident pion energies and for every meson scattering 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 is beyond the peak of the S_{11} (1535) resonance. Measurement of the cross sections needed to obtain R_{π} are planned at incident pion energies that span the range of the channel, $P_{\pi} = 570$ -750 MeV/c. 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 $nn\eta$ and $pp\eta$ coupling constants. The effects due to π^0 - η mixing are expected to be largest near threshold and will be of great interest.

The "superratio", given by R_{η}/R_{π} , will yield a test of charge symmetry in which the beam normalizations will divide out. The primary concerns for the relative normalization of π^+ and π^- beams are the different electron contaminations.

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 would 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 .

The ratios R_{η} and R_{π} will be obtained by measuring the relative η and π^0 yields due to π^+ and π^- and interactions in deuterium. The η and π^0 are detected via their $\gamma\gamma$ decay mode using the η spectrometer from Los Alamos. An exploded view of the

device is shown in Fig. 1. The device has been repaired and was installed in the C-8 line of the AGS last summer. The experience of the ACU investigators with similar spectrometers (the π^0 spectrometer and the NMS) will be 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).

A 300-hour test run using a CD_2 target was conducted in July 1993 to demonstrate the feasibility of the experiment. Two ACU students, Tomo Moriwaki and John Keyser, spent the summer at Brookhaven working on the monitor detectors, participating in the run, and analyzing the data. Aljosa Marusic, a RBI graduate student who will be the thesis student on the experiment, was also given travel support. Sadler spent three weeks at BNL before and during the early part of the test run, leaving after one week of beam to go to Los Alamos for Exp. 1268.

The η spectrometer has a single converter (one radiation length of BGO) and a NaI calorimeter (4x4 array, 16 r. l. thick). Runs were taken in which the trigger did not require a conversion in the BGO. The hope is that since the opening angle of the $\eta \rightarrow \gamma\gamma$ decay is large ($\sim 135^\circ$) then the calorimeter information alone will result in adequate invariant mass resolution. An increase by a factor of 5 in the event rate will result if this relaxed trigger is adequate. Data were taken with C, CH_2 and CD_2 targets and are presently being analyzed by the UCLA group.

Emphasis was placed on the installation and performance of the elaborate setup for monitoring of the pion beam. A pair of scintillators views a beam scintillator at 50° to be sensitive to πp elastic scattering. This is the symmetric scattering angle for both pions and protons from $\pi^\pm p \rightarrow \pi^\pm p$ at 730 MeV/c. This design will make the monitor less sensitive to beam alignment. The πp monitors produced symmetric ADC and TDC spectra, as expected.

Another set of six monitors were situated to be sensitive to πd elastic scattering. These were pairs of scintillators identical to the πp monitors. Two pairs were placed at 55° to view the symmetric scattering for $\pi^\pm d \rightarrow \pi^\pm d$ and four other pairs were to measure scattering for $\theta_\pi = 140^\circ$, $\theta_p = 15^\circ$. Since $\pi^\pm d \rightarrow \pi^\pm d$ is also charge-symmetric, this reaction is a good one to use as a monitor. One of the intense activities preceding the run was the construction of the support system to mount the seven monitor pairs around the η spectrometer.

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 $\pm 0.3\%$. 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 $4-6^\circ$ 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.

Another test done last summer was to use the neutron counters and their veto counters as an E- ΔE detector to detect protons from $\pi^+d \rightarrow pp\eta$. This scheme is being investigated to produce tagged η 's for rare decay studies. The preliminary results obtained with the CD_2 target show clear proton bands in the pulse height spectra of ΔE vs. E . Analysis of these data is being conducted by UCLA.

Plans for the 1994 run are described in the application for renewal. A new beam tune is being developed for the C-8 channel and the data acquisition system is being upgraded by BNL. Preliminary results indicate that the η spectrometer and the beam monitoring are satisfactory to complete the CS ratios described above.

Figure 1. Elements of the Eta Spectrometer

B. N* Collaboration at CEBAF

ACU is a member of the N* collaboration at CEBAF, which plans to utilize the CEBAF Large Aperture Spectrometer (CLAS). An overview of the CLAS is shown in Fig. 1 and 2, taken from CEBAF Conceptual Design report [1]

Among the proposals that have been approved are:

- *Electroproduction of the $\Delta(1232)$ Resonance*, V. Burkert (CEBAF) and R. Minehart (Virginia), spokespersons,
- *Measurement of Polarized Structure Functions in Inelastic Electron Proton Scattering using the CLAS*, V. Burkert, spokesperson,
- *Measurement of $p(e, e'\pi^+)n$, $p(e, e'p)\pi^0$, and $n(e, e'\pi^-)p$ in the 2nd and 3rd Resonance Regions*, Minehart, Burkert and M. Gai (Yale), spokespersons,
- *A Study of the $S_{11}(1535)$ and $P_{11}(1710)$ in $p(e, e'p)\eta$* , S. Dytman (Pittsburgh) and K. Giovanetti (James Madison), spokespersons, and
- *A Measurement of the Electron Asymmetry in $p(e, e'p)\pi^0$ and $p(e, e'\pi^+)n$ in the Mass Region of the $P_{33}(1232)$* , Burkert and Minehart, spokespersons.

The physics is closely related to the research that ACU has been involved in for more than a decade. The extension of our research program to study higher-mass resonances than were accessible with LAMPF pion beams is discussed in the renewal application.

ACU was first invited to join the N* collaboration in 1989 as participants from the hadron community. Discussions were held with the spokespersons for the experiments (V. Burkert of CEBAF, R. Minehart of Virginia, S. Dytman of Pittsburgh and P. Stoler of Rensselaer) regarding ACU's commitments at the time and the possibilities for future participation. It was generally agreed that serious ACU involvement starting in 1992 or 1993 would be acceptable.

Two specific areas of involvement were begun in 1993: 1] participation in the modelling of the CLAS (using GEANT) and 2] providing student help to work on the testing and assembly of the detector elements of the CLAS. Two students, Andrew Rose and Skip Fryar, spent 12 and 10 weeks, respectively, at CEBAF. Two other students, Terry Thomas and Craig Collins, worked three weeks apiece toward the end of the summer on the mass production of fiber light guides for the scintillation counters shown in Fig. 2.

Rose is working on a computer program which merges a hadron event generator (CELEGS, for CEBAF Large Acceptance Spectrometer Event Generator) with the GEANT code used to model the CLAS. A sample event from his code, which models $ep \rightarrow eN^*(1535)$ is shown in Fig. 3. The GEANT output shows an outgoing electron trajectory through the three regions of drift chambers, Cerenkov counters, scintillation counters and calorimeter. A 3-d view, also an output from GEANT using the Decstation 5000 at ACU (see Sec. V-D), is shown in Fig. 4. This view is looking upstream into the electromagnetic shower calorimeter.

Parts of the existing code were updated (e. g., a new coil shape and a redesigned Cerenkov counter). Modifications to the code are done so that everything

remains compatible with existing software. Strict adherence to the CLAS event format will be followed so that the code can be used to make trigger decisions and to simulate the background using software that has already been developed or will be developed by others.

CELEG has been ported to an IBM RS 6000 (a task which was made possible by Andrew Rose's summer work). In addition, it has been modified to control event generation for GEANT running on 32 workstations at one time. The idea is that as CELEG generates events, it sends consecutive events to different workstations to simulate. The results then get sent back to the original CELEG program, which writes them out and creates histograms.

A report on Rose's CELEG/GEANT work is in preparation for submission to the CLAS Electronic Newsletter (Larry Dennis, Florida State U., editor). It is a good example of what an undergraduate can accomplish as part of a large collaboration if given the opportunity.

A detailed performance of the detector is needed to model real physics events (including background) to evaluate the total acceptance of the nearly 4π detector. This project is not a simple one and will require a continuous involvement over several years. Such an involvement is not typical for a summer appointment for an undergraduate student or, for that matter, by one of the investigators who has teaching responsibilities during the academic year. It is deemed possible by a qualified graduate student, supervised by the principal investigators. With the anticipation of production beam at CEBAF in 1995-96, the possibility exists of involving a thesis student supported by this grant.

Reference:

1. *Conceptual Design Report, Basic Experimental Equipment*, Continuous Electron Beam Accelerator Facility. Copies available from CEBAF, 12000 Jefferson Ave., Newport News, VA 23606.

Figure 1. The CLAS toroidal magnetic and support structure. Adapted from Ref. 1

Figure 2. Midplane slice of the CLAS detection system from Ref. 1. The region 2 drift chambers are inside the magnetic torus shown in the previous figure.

Figure 3. Sample electron event from the CELEG/GEANT program.

Figure 4. GEANT output showing a 3-d view of the CLAS looking upstream into the calorimeter and showing the scintillation counters around the periphery.

V. Additional Contributions

A. Participation by ACU Students

Extensive participation by ACU undergraduates has been an unique aspect of this research program from its inception. A list of students who have completed more than one month of full-time involvement is given in Table 1. The following statistics are compiled from these 39 research participants:

- 19 have continued in graduate studies
 - 6 completed doctorates
 - 3 completed Master's degrees
 - 10 currently enrolled in Ph. D. programs
- 7 accepted employment in industry, government, NASA or Los Alamos
- 1 went immediately into high school teaching.
- 12 future graduates ('94 - '96)

Typical tasks for in which the undergraduate participants have been particularly useful are staging of experiments and assembly of apparatus, pulling shifts on experiments, detector development and construction (e.g., the NMS involvement), data analysis (usually at ACU), and writing task-specific software. Advanced tasks for some participants have included major responsibility for some part of the analysis, developing new techniques or computer codes for data analysis (e.g., the tomography project), writing the data acquisition software for experiments, Monte-Carlo simulation, and detector design.

ACU has recently started an honors degree program in which an undergraduate thesis is required. Two students have completed honors theses under the principal investigators: *Monte-Carlo Simulation for the Acceptance of Neutrons from the $\pi^+p \rightarrow \eta n$ Reaction Near Threshold* by Jason Phillips and *Computed Tomography of Cesium Iodide Crystals with Cosmic Muons: a Three-Dimensional Uniformity Response Obtained with Convolutions* by Tyson Browning. Presently, four other students are preparing theses: Keith Elmore on the tomography analysis, Andrew Rose on the modelling of the hadronic background of the CLAS at CEBAF, Gavin Williams on the PC interface to the qVt multichannel analyzer, and John Keyser on the efficiency as a function of time and position of the silicon-strip detectors used in FNAL E789.

The undergraduates have earned favorable reputations at Los Alamos, Fermilab, PNPI, BNL and CEBAF. Last summer marked the largest number of students (11) that were involved at one time. Most of the support was provided from this grant, but three students were supported fully by P-2 at LANL and six others received partial support from MP division at LAMPF. Laboratories where ACU students participated in 1993 were Los Alamos, BNL and CEBAF.

Abstracts of talks given by past students are given in the next section.

Table 1. ACU Undergraduate Research Participants
(More than one month of equivalent full-time involvement)

<u>Student</u>	<u>Year</u>	<u>Upon Graduation</u>
Allen Rose	1980	Ph.D., Arkansas
Mark Tate	1981	Ph.D., Princeton
Thad Walker	1982-83	Ph.D., Princeton
Steve Adrian	1983-84	Ph.D., George Washington
Glenn Olah	1983	Ph.D., Rice
Scott Graessle	1984-85	Ph.D. program, University of Texas
Kaleen (Smith) Graessle	1984-85	High school physics teacher (Austin)
Keith Mitchell	1984-85	M. S., Texas Tech
Terry Black	1984-85	Kodak, Rochester, NY
Stephen Hall	1986	Balcones Research Center, UT Austin
Leif Morton	1986	NASA, Orlando, FL
Stephen Loe	1986, 1989	Ph.D. program, U. Pennsylvania
Derek Lane	1986-1989	Ph.D. program, Iowa State
Meade Brooks	1987-88	M. S., Texas Tech
Lester Towell	1988-89	Physics instructor, U. S. Navy, Orlando
Rusty Towell	1988-89	Math-Physics instructor, U. S. Navy, Orlando
Vicki (McVeigh) Erkkila	1988	Ph.D., UT-Austin
Karlton Powell	1989	M. S., UT-Arlington
Geoff Brown	1989-90	Ph.D. program, Texas A. & M.
Randy Schwindt	1989-90	Ph.D. program, Texas A. & M.
Tony Hill	1989-90	Ph.D. program, Iowa State
Randy Schnathorst	1989-91	Ph.D. program, Purdue University
Jason Phillips	1990-91	Ph.D./M.D. program, UT (M.D. Anderson)
Scott Garner	1990-92	Los Alamos National Laboratory
James Redmon	1990-92	Ph.D. program, Texas Tech
Tyson Browning	1991-92	Ph.D. program, MIT
Keith Elmore	1991-92	Los Alamos National Laboratory
John Keyser	1991-93	1994 Graduate
Gavin Williams	1991	1994 Graduate
Greg Loe	1992-93	1994 Graduate
Andrew Rose	1992-93	1994 Graduate
Tomohiro Moriwaki	1992-93	1994 Graduate
Jake Caire	1993	1995 Graduate
Craig Collins	1993	1995 Graduate
Sean Dodson	1993	1995 Graduate
Skip Fryar	1993	1996 Graduate
David Rigsby	1993	1996 Graduate
Terry Thomas	1993	1995 Graduate
Joshua Willis	1993	1996 Graduate

B. Abstracts of Presentations Given by ACU Students

The following are abstracts submitted to the Texas APS meetings by students supported by this grant during 1992 and 1993:

Data Preparation for Evaluating the Three-Dimensional Uniformity Response of Csl Crystals Using Cosmic Muons. Keith Elmore, Tyson R. Browning, M.E. Sadler, Abilene Christian University. — Jim Amann, Los Alamos National Laboratory. — Abilene Christian University, in conjunction with Los Alamos National Laboratory's Meson Physics Facility, has built and used a crystal tomography apparatus that uniformly illuminates test crystals with cosmic muons in order to determine their three-dimensional response function. A principal improvement of this experiment over the previous experiments by Dowell et al.¹ is the use of drift chambers to improve the position resolution information for the incident muons. In order to take advantage of the increased resolution, careful calibration had to be done to remove the left-right ambiguity from the drift chambers and to calculate accurate spectra for drift times and drift positions which are used in computing the crystal's response function. The methods for determining these calibrations—using software compatible with the laboratory's Q system—will be presented, showing how the correct calibrations have improved the drift chamber spectra and provided better information for determining the crystal's three-dimensional response.

¹D.H. Dowell, et al., Nucl. Inst. and Meth. **A286**, 183 (1990).

A Three-Dimensional Uniformity Response. Obtained with Convolutions. to Cosmic Muons in Csl Crystals. Tyson R. Browning, Keith Elmore, M.E. Sadler, Abilene Christian University. --Jim Amann, Los Alamos National Laboratory. --Abilene Christian University, in conjunction with Los Alamos National Laboratory's Meson Physics Facility, has developed a crystal tomography apparatus that builds on an earlier experiment by Dowell, et al.¹ by improving the solid angle of acceptance of muons to the apparatus and by increasing the resolution of muon trajectory determination through the use of drift chambers. To obtain a 3-D crystal uniformity analysis, an imaging algorithm is required. Such an algorithm will be presented, based on convolution techniques (a standard method of image reconstruction known as Ramachandran's algorithm²). The convolution method is superior to using Fourier transforms in accuracy and in speed, increasing relatively in speed when greater resolution is required². The technique is similar to that used by Dowell, et al.¹, but has been researched and adapted for our geometry and for our improvements in resolution. This project is still underway: results obtained thus far will be shown.

¹D.H. Dowell, et al. *NIM* **A286** (1990) 183-201.

²G.N. Ramachandran and A.V. Lakshminarayanan. *Proc. of the Nat. Acad. of Sciences* USA **68** (1971) 2236-2240.

Identification of the η -Meson Production in the $\pi^-p \rightarrow \eta n$ Reaction at the Saint Petersburg Nuclear Physics Institute. Scott Garner, J. Phillips, M. Sadler, Abilene Christian University.-B. Nefkens, J. Price, D. White, University of California at Los Angeles.- S. Kruglov, I. Lopatin, V. Bekrenev, V. Abaev, A. Mayorov, Saint Petersburg Nuclear Physics Institute. - The η -meson production in the reaction $\pi^-p \rightarrow \eta n$ was observed at the Saint Petersburg Nuclear Physics Institute in July 1991.

Measurements of this process were made by a collaboration of United States and Russian physicists to verify the SPNPI P(beam) and ΔP (beam). Plastic scintillators were placed in front of and behind a liquid hydrogen target, a cylinder 10 cm in diameter. A π^- beam 3.5 cm wide by 1.5 cm high (FWHM) and $\Delta P/P = 0.75\%$ was passed through the target. A pion passing through the upstream counter only signified its interaction within the target. The upstream counter also served as the "start" for a neutron time of flight measurement. The "stop" was the detection of a neutron in one of the six neutron counters, placed 4.71 m from the target at 1, 2, 3, 5, 6, and 7 degrees from the beam axis. TOF spectra were taken using a P(beam) ranging from 670 to 720 MeV/c at these six angles. These TOF spectra showed peaks corresponding to π^+ and η production.

Monte Carlo Simulation of the Acceptance for Neutrons From the $\pi^-p \rightarrow \eta n$ Reaction Near Threshold Jason Phillips, S. Garner, M. Sadler, Abilene Christian University.-B. Nefkens, J. Price, D. White, University of California at Los Angeles.- S. Kruglov, I. Lopatin, V. Bekrenev, V. Abaev, A. Mayorov, Saint Petersburg Nuclear Physics Institute. - The geometrical acceptance for neutrons from the $\pi^-p \rightarrow \eta n$ reaction has been modeled to analyze the results presented in the preceding talk. The Monte-Carlo program selects a beam particle from a phase space (spatial and momentum distribution) defined by the user. An interaction point within the 10-cm-diameter cylindrical target and a random center-of-momentum scattering are selected. The acceptance for these neutrons by six forward-angle (1° - 7°) neutron counters is determined by the ratio of the number of hits to total events. These calculations were done at 687 MeV/c (threshold) to 720 MeV/c. The results were then weighted by the cross section which was assumed to be a linear function of center of mass momentum and then compared to the actual measurements taken at SPNPI. Use of this technique to determine the centroid and width of the beam momentum distribution will be discussed. Plans for future simulations in this program, including the acceptance for gamma rays from either π^+ or η decay, will be discussed.

Monte Carlo Modeling of the Absolute Solid Angle Acceptance in the LAMPE PI0 Spectrometer, J.A. Redmon, L.D. Isenhower, M.E. Sadler, Abilene Christian University, Meade Brooks, Texas Tech University. --- The PI0 Spectrometer is used to measure the individual energies of the two gamma rays produced by π^0 decay. With these energies and the opening angle between the two gamma rays, the energy of the π^0 can be calculated. An absolute calculation of the solid angle is needed for differential cross section calculations. Using Monte Carlo modeling, the laboratory setup is scrutinized by changing various parameters in the simulation runs. This model is compared with actual data obtained by experiment. Using this comparison, it is possible to determine any deviations in the laboratory setup. With the deviations known, an absolute solid angle acceptance can be computed. Parameters varied are the following: 1) Beam Energy, 2) Beam Position in the X and Y direction relative to the target, and 3) Target Position in the Z direction relative to the pivot between the two arms of the spectrometer. These variations are made for beam energies of 10, 20, and 40 MeV at laboratory scattering angles of 0 and 180 degrees.

Measuring Velocity with the "Optic Boom": The Contribution of the Ring Imaging Cerenkov Detector to the Search for Charmless Beauty Decay at Fermilab. Randy Schnathorst and the E789 collaboration (Abilene Christian U., FNAL, Institute of Physics-Taiwan, LANL, Lawrence Berkeley, Northern Illinois U., U. of Chicago, U. of South Carolina). - A charged particle traveling in a medium with a speed exceeding the speed of light in that medium produces Cerenkov radiation (light). This effect is, in a very loose sense, the optical analogue of a sonic boom. The light is emitted at a specific angle, θ , determined by the velocity, β , of the particle according to the equation $\beta = 1/(n \cos \theta)$ where n is the index of refraction of the medium. In the Ring Imaging Cerenkov Detector (RICH), light emitted at an angle θ is focused as a ring of radius $r = f \tan \theta$ (f =focal length) onto a detector. The velocity of the particle is calculated from the radius of the circular ring of light striking the detector, allowing the mass of the particle to be determined. E789 makes use of the well-known E605 RICH detector to study D- and B-meson decays. The physics explored by E789 and the operation of the RICH will be described, and images produced by analysis of data from the RICH will be presented.

Tomography Apparatus for the Evaluation of the Three-Dimensional Response of Scintillation Detectors Using Cosmic Muons. Keith Elmore, Tyson R. Browning, M.E. Sadler, Abilene Christian University. - Jim Amann, Mark Whitton, Los Alamos National Laboratory. - Many physics experiments use scintillation detectors such as NaI, CsI and BGO as calorimeters to measure the energy of particles. The energy resolution has been limited either by the ability of the crystal to contain the produced electromagnetic showers or by the limits set by the number of photoelectrons produced in the photomultiplier. Concern has recently arisen regarding the uniformity of response for any given scintillator. The question of uniformity becomes extremely important when the scintillators will be used in large detector arrays, such as spectrometers. Tomography techniques which allow a 3-dimensional analysis of crystals will be discussed, both past efforts¹ and improvements. The new ideas have been implemented in an apparatus currently being used to analyze the 3-D response of CsI crystals (to be incorporated into the Neutral Meson Spectrometer being built at LAMPF). This talk will discuss these concepts and will be followed by a presentation of the apparatus and techniques needed to make these analyses.

¹ D. H. Dowell, et al., Nucl. Inst. and Meth. **A286**, 183 (1990).

Data Acquisition and Analysis for a Tomography Apparatus for the Evaluation of the Three-Dimensional Response of Scintillation Detectors Using Cosmic Muons. Tyson R. Browning, Keith Elmore, M.E. Sadler, Abilene Christian University.--Jim Amann, Mark Whitton, Los Alamos National Laboratory.--An apparatus has been built and is currently being used to analyze the 3-D response of CsI crystals which will be incorporated into the Neutral Meson Spectrometer being built at LAMPF. With the setup, the response from volumes as small as one cubic centimeter can readily be analyzed. This talk will continue the ideas presented in the previous talk, discussing the apparatus and electronics needed to make these analyses. Furthermore, the data acquisition devices and software used will be explained. Methods of analyzing the data using Fourier transform techniques will be discussed. This project is still underway: results obtained thus far will be shown; status and future directions will be presented; applications for future use will be discussed and solicited.

C. Detector Tomography Facility

Keith Elmore contributed to this section.

Since the summer of 1990, ACU has worked with scientists from the Los Alamos National Laboratory on testing CsI crystals for the Neutral Meson Spectrometer (NMS). During this past year, all remaining crystals were tested and the experiment has been used as the topic of two Senior Honor's Projects. The tomography facility incorporates arrays of scintillators and wire chambers to tag cosmic muons that pass through a crystal under test. By recording the detector signals from the random trajectories of cosmic rays and obtaining adequate counting statistics, two- and three-dimensional responses of the detector crystal can be obtained - the latter through convolution techniques.

The detector response depends on the light collection and uniformity of the crystal. The objective of this project was to determine the performance of individual scintillation detectors before including them in a large, multi-detector array such as the NMS. The key factor in the performance is simply the amount of light that reaches the photomultiplier tube as a function of the location in the detector where the energy of a particle is deposited. For example, if one region of a detector produces 10% more light than another region then the resolution is limited to this level even if the statistics (determined by the number of photoelectrons produced at the photocathode) would indicate that a much better resolution, typically on the order of a few percent, could be obtained. Geometric factors such as the size of the crystal and of the photomultiplier tube are of prime importance. Another factor is the nonuniformity induced by the crystal growth method.

The tomography concept is very similar to Computer-Aided Tomography (CAT), where a collimated x-ray beam is passed through an object (or a patient) from various directions. The transmission information is then deconvoluted using Fourier transform techniques to obtain the density distribution of the material. Three-dimensional information ranging from cracks in welds to tumors in patients is obtained. The detector tomography principle described here is similar, except that information on the detector response is obtained for particles traversing the active volume. A schematic is shown in Fig. 1. The apparatus is triggered by a two-fold coincidence between either of the two scintillators and any one of the crystals being tested, indicating the presence of a cosmic muon. The trajectory of the muon both before and after passing through a test crystal is obtained from x-y wire chambers above and below the crystal. The random nature of the incident cosmic rays insures that the crystals are uniformly illuminated along a large number of trajectories. The solid-angle acceptance of the apparatus is such that all portions of the crystal can be tested without having to rotate either the apparatus or the crystal, thus eliminating the problem of accurately determining the position of the crystal a second time. However, rotation of the crystal does provide a check of the systematic accuracy of a scan. Such a tomography system is discussed in Ref. 1, the primary difference being that scintillation counter hodoscopes (small strips of scintillator to give position information) were used instead of drift chambers. The present system gives much better position resolution ($\sim 200 \mu\text{m}$) of the muon trajectories than that afforded by the hodoscopes of Ref. 1 (3.8 cm).

Work on the apparatus began during the summer of 1990 when four wire chambers (two with a single pair of x-y planes and two with double x-y planes) were constructed in Los Alamos by ACU students Scott Garner and Jason Phillips. These chambers, described in Ref. 2, are of the design used at EPICS and HRS at LAMPF. That fall, a used Microvax II computer was purchased by ACU for data acquisition and was subsequently taken to Los Alamos. At that time, a request was made to begin construction of the scintillators and light guides for the apparatus. In May 1991, two students (Tyson Browning and Keith Elmore) returned to Los Alamos to work full time on the project. During the summer of 1991 a light tight box was designed and built. The trigger scintillators were assembled and mounted for easy removal for loading/unloading crystals. All of the electronics was obtained and the system was assembled in the Biomed control room which had been reserved for the tests.

During this first operation, a small sample of crystals was tested and initial software development was done. The first step of finding the energy deposition per unit path length required a program to calculate the path length through any portion of a crystal. This software must take into account that the crystals were tapered. Browning was responsible for a significant part of the software development for the system.

Elmore and Browning continued their work by incorporating aspects of the data analysis into their Senior Honor's theses. Elmore's work and thesis covers preparing the data for analysis, where a great deal of calibration is needed for the signals from the drift chambers. Accuracy in the drift time and drift distance histograms computed from this information was vital in order to achieve the maximum position resolution provided by the chambers. The work of determining the appropriate calibrations has been done using software compatible with LAMPF's Q-system. After achieving acceptable calibrations, the data were replayed and output in a form appropriate for the determination of the three-dimensional response of the CsI crystals. The project is substantially completed, but Elmore is replaying a series of long runs from this past summer to get high statistics data for use in his report. Enough data were not available at the time Browning finished his report to reduce the statistical uncertainty to the level desired.

Browning's work [Ref. 3] focused on researching various methods for producing the three-dimensional response. After comparing several possibilities, a method based on convolution techniques (a standard method of image reconstruction known as Ramachandran's algorithm [Ref. 4]) was chosen. The convolution method is superior to using Fourier transforms in accuracy and in speed, since it involves summations over one variable at a time, whereas a two-dimensional reconstruction using Fourier transforms requires double summations. Hence, the convolution method is much faster, increasing relatively in speed when greater resolution is required [Ref. 4]. Browning implemented this algorithm in FORTRAN code. The end result of his procedure is a three-dimensional plot showing the percent non-uniformity for a given slice of the crystal being tested. A representative plot of the result is included as Figure 2.

Final testing of the last shipment of CsI crystals at Los Alamos was completed in early summer of 1993. Shortly thereafter, the apparatus was brought back to Abilene

and re-assembled to be used in the nuclear and particle physics laboratory at Abilene Christian University. However, it was mid-October (the end of the beam cycle at LAMPF) before the necessary electronics could be borrowed to get the complete system running in Abilene. After obtaining the necessary electronics, the system was able to collect data.

The tomography apparatus has been shipped and is being installed at the Paul Scherer Institute (PSI) in Zurich, Switzerland. Dinko Pocanic from the University of Virginia, the experiment spokesperson for a new measurement of pion beta decay at PSI, requested the use of the apparatus to test CsI crystals for the π^0 detector. The equipment was disassembled and shipped in November and will remain at PSI for approximately six months.

References:

1. D. H. Dowell, A. M. Sandorfi, A. Q. R. Baron, O. C. Kistner, G. Matone, C. E. Thorn and R. M. Sealock, Nucl. Inst. and Meth. **A286**, 183 (1990). This article describes the only known application of computed detector tomography with cosmic muons. The wire chambers used to trigger data collection in the proposed apparatus will provide a more precise determination of the muon trajectories.
2. L. G. Atencio, J. F. Amann, R. L. Boudrie and C. L. Morris, Nucl. Inst. and Meth. **183**, (1990). The drift chambers used for this project are of the design described in this article.
3. Tyson R. Browning. *Computed Tomography of Cesium Iodide Crystals with Cosmic Muons: A Three-Dimensional Uniformity Response, Obtained with Convolutions*. Senior Honor's Project Abilene Christian University (1993).
4. G.N. Ramachandran and A.V. Lakshminarayanan. *Proceedings of the National Academy of Sciences USA* 68 (1971) 2236-2240. This article describes the convolution algorithm used (with adaptations) to get the three-dimensional uniformity response.

NMS TOMOGRAPHY SETUP

Plan View--Not to Scale

Figure 2: Csl % Deviation from Standard Uniformity

D. Computer Upgrades and Capabilities at ACU

The investigators have given high priority to on-site computing capability at ACU. Until now, this effort has entailed purchasing hardware and software which were compatible with LAMPF computing facilities. This compatibility, particularly with the LAMPF 'Q' system, has enabled the replay of the data tapes from LAMPF Expts. 363, 806 and 882 to be completed in Abilene. Using \$1500 from this grant, a used Microvax 3600 was purchased in the spring of 1993 from the ACU academic computing division. This computer, which was placed in the physics department, has been the machine on which the tomography analysis discussed in the previous section has been accomplished. As part of an agreement to move the main academic computer (a Microvax 4000) to a different building, the university has provided a 9-track tape drive, a SCSI controller, and installed ethernet capabilities on the Microvax. With the 3600 and SCSI controller, the researchers were able to attach an 8-mm tape drive previously attached to the academic computing facilities (but had been purchased under this grant in 1992). In addition, a 2 gigabyte SCSI disk drive was purchased under this grant to provide enough disk space to spool the data from the 8-mm tapes and old 9-track tapes. The present setup gives physics faculty and students 24-hour access for mounting data tapes. Data analysis tasks have generally been faster in real time compared to previous computing capability because of the smaller load on the machine. The Microvax 4000 is still used remotely, and the ethernet link is used for rapid exchange of data files from one machine to the other. Both Vaxes are also used as file servers for the Macintosh computers (of which five have been purchased under this grant) through Ethernet and Appletalk communication networks.

The tomography analysis is only one of the tasks being done on the 3600. Jimmy Redmon, an ACU physics graduate presently enrolled in graduate study at Texas Tech, has been using the computer to analyze the 90° data from experiment 882 for his master's thesis. Additionally, data from LAMPF Exp. 1268 are being analyzed, and the tape and disk capabilities have been used to copy data from old 9-track tapes to the 8-mm tapes.

A Unix-based system, a Decstation 5000/200, has been acquired by the physics department. Analysis software from CERN has been installed on both the Decstation and the Vax systems. These packages include PAW (Physics Analysis Workstation), HBOOK and the analysis libraries. In the past year funds from this grant have been used to purchase an 8-mm tape drive and a 2 gigabyte disk for this system also.

The Decstation has been used for the analysis of the PNPI data discussed in Sec II-D. First the raw data tapes were converted from EBCDIC format (an old IBM standard). N-tuple files were then created from the TDC, ADC and beam hodoscope information. Once the data are in N-tuple format, PAW can be used to plot graphs and obtain yields which satisfy certain conditions (e.g., a cut on pulse height or TOF).

The Decstation is also being used to run the CELEGS/GEANT Monte-Carlo to model the CLAS at CEBAF (discussed in Sec IV-B). This system will become even more useful as the group becomes more familiar with the Unix environment. It is anticipated that the machine will become the main computer for analysis of data at ACU for the new programs at BNL, FNAL and CEBAF.

E. Testing of the Cesium-Iodide Crystals for the NMS

Andrew Rose contributed to this section.

Starting in summer 1992, shipments of Cesium Iodide crystals and phototubes for the NMS calorimeter were tested in two ways. The first was a test of the fast/slow components of the crystals. Excessive slow components would make the CsI crystals unusable for the NMS high rate environment. The second test procedure utilized the tomography system described above.

A shielding block that was being moved after the 1992 run was dropped onto one arm of the NMS, necessitating the replacement of most of the crystals. Crystal testing resumed in summer 1993 on the replacements.

For the latter tomography measurements, several ACU students developed a way to accurately and reproducibly position the crystals in the box before collecting data. The positioning problem was solved by the use of plastic dividers which packed the crystals tightly together. After this problem was solved, we began to take data on eight crystals at a time with "runs" of twelve hours each. Each crystal was tested in two positions; the second orientation was a rotation of 90° (along the crystal's long axis) from the first. We had obtained data on seventy-two of the crystals by the end of the summer.

Several students also worked on testing the overall performance of the crystal and photomultiplier tube assemblies. The setup and procedures were almost identical to those of the former test. A standard crystal was used to test the photomultiplier tubes, and a standard tube was used to test the new crystals. The apparatus and procedure were simple: the crystal/tube unit was placed in a light-tight box and then data were taken on its response to a ^{137}Ce source and cosmic radiation. The cosmic spectrum was then subtracted out of the ^{137}Ce spectrum to minimize the error.

Measurements of the fast-to-total ratio and energy resolution were made for all crystals. The fast-to-total ratio was obtained by comparing the light output using two ADC's of different gate widths (100 ns and 1 μs). The crystal resolution was determined using the 0.662 MeV γ rays from ^{137}Ce . Defining the resolution as

$$R = \frac{\text{Full width at half maximum}}{\text{Centroid}}$$

the photoelectrons per MeV (at the tube photocathode) were determined from

$$\frac{\text{Pe}}{\text{MeV}} = \frac{2.354^2}{R^2}(0.662).$$

Initially, the failure rate of the CsI crystals was near 50%. The defective crystals were shipped back to the manufacturer, Horiba Corporation. All of the crystals from the latter shipments passed the tests. The final 120 crystals were all deemed acceptable.

The photomultiplier tubes, on the other hand, demonstrated a wide range of values for the Pe/MeV figure. All but the very best of the tubes were disappointing, and many were initially rejected. The 120 best tubes were used with the understanding that EMI, the manufacturer, would replace the tubes that were not up to specifications.

Figures 1 and 2 show the pulse height histograms of both a good and bad tube in the ^{137}Ce tests. Figure 1 is the good tube. The uninteresting spikes at each of end of the histograms represent the ADC pedestal and end of conversion. The highest-energy-peak is the 0.662 MeV γ from ^{137}Ce . The peak immediately to the left of the Cesium peak is the background which is subtracted out before the calculations are done. The small peak near threshold is the darkcurrent or tube noise. Note the relative heights of the γ peaks and noise peaks in Fig. 1 and 2.

Figure 1. ^{137}Ce pulse height measured with a good tube.

Figure 2. ^{137}Ce pulse height measured with a bad tube.

F. The qVt-to-PC Interface

The qVt (manufactured by LeCroy Corporation) is the most popular multi-channel analyzer at all of the nuclear and particle physics laboratories where this group has research activity. It is used for simple setup and testing procedures where a computer-based data acquisition system is not needed. Its advantages for multi-channel analysis of one-dimensional spectra are 1) compactness, 2) ability to analyze charge (q), voltage pulse height (V) or time difference (t) for signals in a single unit, and 3) ease of use. The primary disadvantages are 1) no on-line analysis (e.g., centroid and width of a distribution) is available, and 2) lack of permanent storage on magnetic media. ACU developed a microcomputer interface between the qVt and a TRS-80 in 1985. This interface have served well but the system stopped operating last Fall of 1992. Instead of repairing the old system (which used a microcomputer no longer being produced), it was decided to develop a new interface which communicated with an IBM-PC-compatible computer.

Gavin Williams designed the new interface as an honors project for the electronics course at ACU. The design was included in last year's progress report. Some bugs have been corrected in the prototype which is constructed on an internal IBM/PC board using wire-wrap for IC connections. The cost of producing a printed circuit board for the design is being investigated. It is hoped to manufacture several boards and make them available to other groups.

Williams is presently writing software for the data acquisition and analysis. This project is the topic of his senior honors thesis. The software will control the qVt, store spectra, manipulate histograms (add or subtract normalized data) and perform functions such as determining the area, centroid and width of a peak. A sample of the hardcopy output (a ^{137}Ce γ spectrum taken with a NaI detector at ACU) is included in Fig. 1 below.

Figure 1. Sample output of the qVt/PC interface software.

VI. Publications:

Submissions and publications in refereed journals, papers presented at professional meetings, and seminar presentations during 1990-93 are listed below in reverse chronological order. Listed separately are publications with Isenhowe as a co-author which resulted from his work during his leave of absence on a NATO fellowship at CERN and his work done as a graduate student at Iowa State University/Ames Laboratory. These articles are listed here since they involve one of the principal investigators.

Articles in Refereed Journals:

Search for the Decay $D^0 \rightarrow \mu^+\mu^-$, 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. Isenhowe, 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, to be submitted to Phys. Rev. D.

Nuclear Dependence of Neutral D-Meson Production by 800 GeV/c Protons, M. J. Leitch, 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. Isenhowe, 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, submitted to Phys. Rev. D.

Production of J/ψ at Large x_F in 800 GeV/c p-Copper and p-Beryllium Collisions, M. S. Kowitt, G. Gidal, P. M. Ho, K. B. Luk, D. Pripstein, L. D. Isenhowe, 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, submitted to Phys. Rev. D.

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.

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. Isenhowe, M. E. Sadler, I. Supek and I. Slaus, to be submitted to Phys. Rev. C.

The Spin Rotation Parameters A and R from π^+p and π^-p Elastic Scattering from 427 to 657 MeV/c, I. Supek, D. B. Barlow, W. J. Briscoe, J. F. Davis, G. J. Kim, D. W. Lane, A. Mokhtari, B. M. K. Nefkens, C. Pillai, M. E. Sadler, C. J. Seftor, M. F. Taragin, J. A. Wightman, Phys. Rev. D **47**, No. 5, 1762 (1993).

On the Extraction of the πNN Coupling Constant from Partial Wave Analysis, J. Stahov, M. E. Sadler and V.V. Abaev, Phys. Rev. Lett. **63**, No. 4, 548 (1992).

Nuclear Effects on Heavy Quark Production Results from Fermilab Experiments E772 and E789, By E772 and E789 Collaboration (M.J. Leitch, et al.), Nucl. Phys. **A544**, 197c (1992).

Search for Neutral Pions from the Spontaneous Fission of ^{252}Cf , J. N. Knudson, C. L. Morris, J. D. Bowman, W. C. Sailor, S. J. Seestrom, I. Supek, M. E. Sadler and L. D. Isenhower, Phys. Rev. **C44**, 2869 (1991).

A Test of Consistency of Low-Energy Pion-Nucleon Differential Cross Sections with Partial Cross Sections, T. S. Hill, Journal of Undergraduate Research in Physics, Vol. 9, No. 2, 53 (May, 1991).

Angle and Energy Dependence of the Superratio for π^+ and π^- Elastic Scattering from ^3H and ^3He : Evidence for Charge-Symmetry Violation, C. Pillai, D. B. Barlow, B. L. Berman, W. J. Briscoe, A. Mokhtari, B. M. K. Nefkens and M. E. Sadler, Phys. Rev. **C43**, 1838 (1991).

Measurement of the Left-Right Asymmetry in $\pi p \rightarrow \gamma n$ from 301-625 MeV/c at Backward Angles, G. J. Kim, J. Arends, W. J. Briscoe, J. Engelage, B. M. K. Nefkens, M. E. Sadler and H. J. Ziock, Phys. Rev. **D43**, 687 (1991).

Superratio and the Simple Ratios of π^+ and π^- Elastic Scattering on ^3H and ^3He at 180 MeV to Investigate Charge Symmetry, B. M. K. Nefkens, W. J. Briscoe, A. D. Eichon, D. H. Fitzgerald, A. Mokhtari, J. A. Wightman and M. E. Sadler, Phys. Rev. **C41**, 2770 (1990).

Analyzing Power for πp Charge Exchange in the Backward Hemisphere from 301 to 625 MeV/c and a Test of πN Partial-Wave Analyses, G. J. Kim, J. Arends, W. J. Briscoe, J. Engelage, B. M. K. Nefkens, M. E. Sadler, M. Taragin and H. J. Ziock, Physical Review **D41**, 733 (1990).

Papers (1990-1993) from Isenhower's Thesis Research and DELPHI Collaboration

A Study of B^0 -anti- B^0 Mixing Using Semileptonic Decays of b Hadrons Produced from Z^0 , By the DELPHI Collaboration (P. Abreu, et al.), Phys.Lett.**B301** 145 (1993).

Evidence for $f_2(1720)$ Production in the Reaction Pomeron-Pomeron $\rightarrow \pi^+\pi^-\pi^+\pi^-$ By Ames-Bologna-CERN- Dortmund-Heidelberg-Warsaw Collaboration (A. Breakstone, et al.), Z. Phys. **C58**, 251 (1993).

A Measurement of B Meson Production and Lifetime Using D -lepton Events in Z^0 Decays, By the DELPHI Collaboration (P. Abreu, et al.), Z.Phys. **C57** 181 (1993).

On the Extraction of the πNN Coupling Constant from Partial Wave Analysis, J. Stahov, M. E. Sadler and V.V. Abaev, Phys. Rev. Lett., Vol. 63, No. 4, 548 (1992).

Design and Performance of the Readout Electronics Chain of the Delphi Forward Ring Imaging Cherenkov Detector, P.Dam, F. Formenti, A. Hallgren, D. Isenhower, P. Kostarakis, D. Loukas, L. McCulloch, B.S. Nielsen, J.C. Tarle, A.S. De la Vega, S. Xyroustikos, IEEE Transactions on Nuclear Science, **39**, 1292 (1992).

Drift optimization for the photon detectors of the DELPHI forward ring imaging Cherenkov detector, B. Bostjancic, O. Botner, L.O. Eek, v. Gracco, A. Hallgren, D. Isenhower, J. Medbo, and J. Michalowski, NIM **A323**, 363 (1992).

Multiplicity Fluctuations in Hadronic Final States from the Decay of the Z^0 , By the DELPHI Collaboration (P. Abreu, et al.), Nucl. Phys. **B386**, 471 (1992).

Measurement of the Partial Width of the Z^0 into $b\bar{b}$ Final States Using their Semileptonic Decays, By the DELPHI Collaboration (P. Abreu, et al.), Z. Phys. **C56**, 47 (1992).

Charged Particle Multiplicity Distributions for Fixed Number of Jets in Z^0 Hadronic Decays, By the DELPHI Collaboration (P. Abreu, et al.), Z. Phys. **C56**, 63 (1992).

A Study of the Decays of τ Leptons Produced on the Z Resonance at LEP, By the DELPHI Collaboration (P. Abreu, et al.), Z. Phys. **C55**, 555 (1992).

Determination of α_s in second order QCD in hadronic Z decays, By the DELPHI Collaboration (P. Abreu, et al.), Z. Phys. **C54**, 55 (1992).

Evidence for B^0_s Meson Production in Z^0 Decays, By the DELPHI Collaboration (P. Abreu, et al.), Phys.Lett. **B289**, 199 (1992).

Bose-Einstein Correlations in the Hadronic Decays of the Z^0 , By the DELPHI Collaboration (P. Abreu, et al.), Phys.Lett. **B286**, 201 (1992).

Measurement of the Z^0 Branching Fraction to b Quark Pairs Using the Boosted Sphericity Product, By the DELPHI Collaboration (P. Abreu, et al.), Phys. Lett., **B281**, 383 (1992).

A Measurement of $\sin^2\theta_w$ from the Charge Asymmetry of Hadronic Events at the Z^0 Peak, By the DELPHI Collaboration (P. Abreu, et al.), Phys. Lett. **B277**, 371 (1992).

Study of Final State Photons in Hadronic Z^0 Decay and Limits on New Phenomena, By the DELPHI Collaboration (P. Abreu, et al.), Z. Phys. **C53**, 555 (1992).

Measurement of the Average Lifetime of B Hadrons, By the DELPHI Collaboration (P. Abreu, et al.), Z. Phys. **C53**, 567 (1992).

A Search for Neutral Higgs Particles in Z^0 Decays, By the DELPHI Collaboration (P. Abreu, et al.), Nucl. Phys. **B373**, 3 (1992).

Search for Excited Charged Leptons in Z^0 Decays, By the DELPHI Collaboration (P. Abreu, et al.), Z. Phys. C53, 41 (1992).

Production of Strange Particles in the Hadronic Decays of the Z^0 , By the DELPHI Collaboration (P. Abreu, et al.), Phys. Lett. B275, 231 (1992).

A Measurement of the $b\bar{b}$ Forward Backward Asymmetry Using the Semileptonic Decay into Muons, By the DELPHI Collaboration (P. Abreu, et al.), Phys. Lett. B276, 536 (1992).

Multiplicity Dependence of Mean Transverse Momentum in e^+e^- Annihilations at LEP Energies, By the DELPHI Collaboration (P. Abreu, et al.), Phys. Lett. B276, 254 (1992).

Searches for Heavy Neutrinos from Z Decays, By the DELPHI Collaboration (P. Abreu, et al.), Phys. Lett. B274, 230 (1992).

Search for Scalar Leptoquarks from Z^0 Decays, By the DELPHI Collaboration (P. Abreu, et al.), Phys. Lett. B275, 222 (1992).

Study of Orientation of 3-jet Events in Z^0 Hadronic Decays Using the DELPHI Detector, By the DELPHI Collaboration (P. Abreu, et al.), Phys. Lett. B274, 498 (1992).

The Reaction $e^+e^- \rightarrow \gamma\gamma$ at Z^0 Energies, By DELPHI Collaboration (P. Abreu, et al.), Phys. Lett. B268, 296 (1991).

The Reaction Pomeron-Pomeron $\rightarrow \pi^+\pi^-$ and an Unusual Production Mechanism for the $f_2(1270)$, By Ames-Bologna-CERN-Dortmund-Heidelberg-Warsaw Collaboration (A. Breakstone, et al.), Z. Phys. C48, 569 (1990).

A measurement of the lifetime of the tau lepton, By DELPHI Collaboration (P. Abreu, et al.), Phys. Lett. B267, 422 (1991).

A study of the reaction $e^+e^- \rightarrow \mu^+\mu^-$ around the Z^0 pole, By the DELPHI Collaboration (P. Abreu, et al.), Phys. Lett., B260, 240 (1991).

Determination of Z^0 Resonance Parameters and Couplings from its Hadronic and Leptonic Decays, By the DELPHI Collaboration (P. Abreu, et al.), Nucl. Phys. B367, 511 (1991).

The Reaction Pomeron-Pomeron $\rightarrow \pi^+\pi^-$ and an Unusual Production Mechanism for the $f_2(1270)$, By Ames-Bologna-CERN-Dortmund-Heidelberg-Warsaw Collaboration (A. Breakstone, et al.), Z. Phys. C48, 569 (1990).

A Sensitive Test of QCD from Parton-Parton Scattering at the ISR CERN, By Ames-Bologna-CERN-Dortmund-Heidelberg-Warsaw Collaboration (A. Breakstone, et al.), Phys. Lett., 248B, 220 (1990).

Papers at professional meetings (presented by first author):

$\pi p \rightarrow \pi^0 n$ Cross Sections in the Region of the Δ Resonance, D. Isenhower, L. Nguyen-Tansill, H. Crannell, J. Redmon, M. Sadler, C. Mertz, J. Wise, J. Connelly, J. Amann, C. Morris, M. Rawool-Sullivan, R. M. Whitton, B. Park, Q. Zhao, P. P. Hui, A. Marusic and I. Supek, Bull. Am. Phys. Soc. **38**, 1818 (1993).

Measurements of Pion-Nucleon Charge Exchange Near the Δ Resonance Using the NMS at LAMPF, M. E. Sadler, et al., Proc. of the 5th International Symposium on Meson-Nucleon Physics and the Structure of the Nucleon, Vol. II, Boulder, Colorado, 6-10 September 1993.

Forward-Angle Cross Sections for Pion-Nucleon Charge Exchange in the Region of the $\Delta(1232)$ Resonance, L. Nguyen-Tansill, H. crannell, D. Isenhower, J. Redmon, M. Sadler, C. Mertz, J. Wise, J. Connelly, J. Amann, C. Morris, M. Rawool-Sullivan, R. M. Whitton, B. Park, Q. Zhao, P. P. Hui, A. Marusic and I. Supek, Bull. Am. Phys. Soc. **38**, 942 (1993).

A Fast Ring-Imaging Cherenkov Counter for a Fixed-Target Heavy-Quark Experiment, 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, June 1-5, 1993.

First Results from the New Neutral Meson Spectrometer at LAMPF, M. E. Sadler, L. D. Isenhower, J. R. Redmon, C. Mertz, H. Crannell and L. Nguyen, J. Amann, R. Boudrie, C. Morris and R. M. Whitton, I. Supek and A. Marusic, Texas Section of the APS, AAPT and SPS, Edinburg, 12-13 March, 1993.

Data Preparation for Evaluating the Three-Dimensional Uniformity Response of CsI Crystals Using Cosmic Muons, Keith Elmore, Tyson R. Browning, M.E. Sadler, and Jim Amann, Texas Section of the APS, AAPT and SPS, Edinburg, 12-13 March, 1993.

A Three-Dimensional Uniformity Response, Obtained with Convolutions, to Cosmic Muons in CsI Crystals, Tyson R. Browning, Keith Elmore, M.E. Sadler and Jim Amann, Texas Section of the APS, AAPT and SPS, Edinburg, 12-13 March, 1993.

Analysis of Locally Non Zero Harmonics in Superconducting Quadrupole Magnets, Jeff E. Arrington, Texas Section of the APS, AAPT and SPS, Edinburg, 12-13 March, 1993.

On the Use of TOSCA for Modeling the Drift Fields of the DELPHI FRICH Detector, by L.Donald Isenhower, paper delivered at the San Marcos Meeting of the American Physical Society, 6-7 March 1992.

Identification of the η -Meson Production in the $\pi p \rightarrow \eta n$ Reaction at the Saint Petersburg Nuclear Physics Institute, Scott Gamer, J. Phillips, M. Sadler, B. Nefkens, J. Price, D. White, S. Kruglov, I. Lopatin, V. Bekrenev, V. Abaev, and A. Mayorov, Texas Section of the APS, AAPT and SPS, San Marcos, Bull. Am. Phys. Soc. **37**, 1906 (1992).

Monte Carlo Simulation of the Acceptance for Neutrons From the $\pi^+p \rightarrow \eta n$ Reaction Near Threshold, Jason Phillips, S. Garner, M. Sadler, B. Nefkens, J. Price, D. White, S. Kruglov, I. Lopatin, V. Bekrenev, V. Abaev, and A. Mayorov, Texas Section of the APS, AAPT and SPS, San Marcos, Bull. Am. Phys. Soc. **37**, 1906 (1992).

Monte Carlo Modeling of the Absolute Solid Angle Acceptance in the LAMPF P10 Spectrometer, J.A. Redmon, L.D. Isenhower, M.E. Sadler and Meade Brooks, Texas Section of the APS, AAPT and SPS, San Marcos, Bull. Am. Phys. Soc. **37**, 1907 (1992).

Measuring Velocity with the "Optic Boom": The Contribution of the Ring Imaging Cerenkov Detector to the Search for Charmless Beauty Decay at Fermilab, Randy Schnathorst and the E789 collaboration, Texas Section of the APS, AAPT and SPS, San Marcos, Bull. Am. Phys. Soc. **37**, 1907 (1992).

Tomography Apparatus for the Evaluation of the Three-Dimensional Response of Scintillation Detectors Using Cosmic Muons, Keith Elmore, Tyson R. Browning, M.E. Sadler, Jim Amann and Mark Whitton, Texas Section of the APS, AAPT and SPS, San Marcos, Bull. Am. Phys. Soc. **37**, 1906 (1992).

Data Acquisition and Analysis for a Tomography Apparatus for the Evaluation of the Three-Dimensional Response of Scintillation Detectors Using Cosmic Muons, Tyson R. Browning, Keith Elmore, M.E. Sadler, Jim Amann and Mark Whitton, Texas Section of the APS, AAPT and SPS, San Marcos, Bull. Am. Phys. Soc. **37**, 1907 (1992).

Comparison of Pion and Electron Inelastic Scattering on ^3H and ^3He Close to Breakup, B. M. K. Nefkens, G. C. Anderson, D. B. Barlow, B. L. Berman, W. J. Briscoe, A. Mokhtari, A. M. Petrov, C. Pillai and M. E. Sadler, Bull. Am. Phys. Soc. **37**, 1303 (1992).

Pion Scattering on ^3He and ^3H in the Non-Spin-Flip Dip, C. Pillai, D. Barlow, S. Greene, B.M.K. Nefkens, R. S. Kessler, G. J. Kim, J. W. Price, I. Slaus, J. A. Wightman, W. J. Briscoe, B. L. Berman, K. S. Dhuga, S. Matthews, M. E. Sadler and K. Smith, Bull. Am. Phys. Soc. **37**, 915 (1992).

Back-Angle Cross Sections for π^- Scattering from ^3H and ^3He near the Δ Resonance, S. J. Greene, W. J. Briscoe, B. L. Berman, R. W. Caress, K. S. Dhuga, S. N. Dragic, S. K. Matthews, N. J. Nicholas, D. B. Barlow, B. M. K. Nefkens, C. Pillai, J. Price and M. E. Sadler, Int. Nucl. Phys. Conf., Wiesbaden, Germany, 26 July-1 Aug., 1992.

Comparison of Elastic Scattering Cross Sections for Pions from ^3H and ^3He in the Backward Hemisphere, S. K. Matthews, B. L. Berman, W. J. Briscoe, R. W. Caress, K. S. Dhuga, S. N. Dragic, D. Knowles, D. Macek, N. J. Nicholas, M. F. Taragin, D. B. Barlow, B. M. K. Nefkens, C. Pillai, J. Price, L. D. Isenhower, M. E. Sadler, S. J. Greene, I. Slaus and I. Supek, Int. Nucl. Phys. Conf., Wiesbaden, Germany, 26 July-1 Aug., 1992.

Measurements of Differential Cross Sections for Pion-Nucleon Charge Exchange at Forward Angles, N. J. Nicholas, W. J. Briscoe, M. F. Taragin, A. Mokhtari, M. E. Sadler, D. Isenhower, I. Supek, V. McVeigh, R. Towell, L. Towell, D. Lane, M. Brooks and A. Donley, Int. Nucl. Phys. Conf., Wiesbaden, Germany, 26 July-1 Aug., 1992.

Forward- and Backward-angle Differential Cross Sections For $\pi^0 p \rightarrow \pi^0 n$ at $T_\pi = 10, 20$, and 40 MeV, M.E. Sadler, B.M. Brooks, L.D. Isenhower, W.J. Briscoe, J.D. Bowman, D.H. Fitzgerald, J.N. Knudson, Presented at the IV International Symposium on Pion-Nucleon Physics and the Structure of the Nucleon, Bad Honnef, Germany, Sept. 9-13, 1991.

Equality Test of Isospin Invariance Using Complete Data Sets for Pion-Nucleon Scattering, M.E. Sadler, Presented at the IV International Symposium on Pion-Nucleon Physics and the Structure of the Nucleon, Bad Honnef, Germany, Sept. 9-13, 1991.

Baryon Resonance Studies at the Proposed PILAC Facility, M.E. Sadler, Presented at the Baryon Spectroscopy and the Structure of the Nucleon Conference held at Laboratoire National Saturne, France, Sept. 23-25, 1991.

Baryon Resonance Studies at PILAC, M. E. Sadler, PILAC User's Meeting at the Spring Meeting of the APS, Washington DC, 24 April 1991.

Operation of silicon microstrip detectors in a high radiation environment, By J.S. Kapustinsky, D.M. Alde, J.G. Boissevain, R.G. Jeppesen, D.W. Lane, M.J. Leitch, J.W. Lillberg, T.A. Lopez, P.L. McCaughey, J.M. Moss, J.C. Peng (Los Alamos), B.M. Brooks, L.D. Isenhower, M.E. Sadler (Abilene Christian U.), L.M. Lederman, M.H. Schub (Chicago U.), C.N. Brown, W.E. Cooper, K. Gounder, Y.B. Hsiung, C.S. Mishra (Fermilab), G. Gidal, M.S. Kowitt, K.B. Luk (LBL, Berkeley), D.M. Kaplan, V.M. Martin, R.S. Preston, J. Sa (Northern Illinois U.), R.L. Childers, C.W. Darden (South Carolina U.), G.C. Kiang, P.K. Teng (Taiwan, Inst. Phys.), FERMILAB-CONF-90-214-E, Oct 1990. 4pp. Presented at Symp. on Detector Research and Development for the Super Collider, Ft. Worth, TX, Oct 15-18, 1990.

Dilepton and dihadron production in proton - nucleus collisions at 800-gev, By E-772 Collaboration and E-789 Collaboration (C.S. Mishra, et al.), FERMILAB-CONF-90/100-E, May 1990. 12pp. Presented at the XXVth Rencontres de Moriond, High Energy Hadronic Interactions, Les Arcs, France, Mar 11-17, 1990.

Performance of a Silicon Microstrip Detector in a High Radiation Environment, C. S. Mishra, C. N. Brown, J. Kapustinsky, M. J. Leitch, P. L. McCaughey, J. C. Peng, W. Sailor, K. Holzschneider and M. Sadler, 15th APS Division of Particles and Fields General Meeting, Houston, 3-6 January, 1990. *Analysis of the Low-Energy $\pi^0 p \rightarrow \pi^0 n$ Experimental Data Taken in Light of Contemporary Theories*, B. M. Brooks, M. A. K. Lodhi, T. J. Black, L. D. Isenhower, D. W. Lane, M. E. Sadler, J. D. Bowman and D. H. Fitzgerald, Fall meeting of Texas Section of the APS, Texas City, 8-10 November, 1990.

Elastic Pion Scattering from ^3H and ^3He at Backward Angles, S. K. Matthews, B. L. Berman, W. J. Briscoe, R. W. Caress, K. S. Dhuga, S. N. Dragic, D. Knowles, D. Macek, A. Mokhtari, N. J. Nicholas, M. F. Taragin, A. Donley, L. D. Isenhower, K. Powell, M. E. Sadler, D. B. Barlow, B. M. K. Nefkens, J. Price, W. R. Gibbs, B. F. Gibson, S. Greene and I. Supek, Bull. Am. Phys. Soc. 35, 945 (1990).

Seminars:

Pion-Nucleon Scattering Around the World, M. E. Sadler, Texas Tech University, Physics Department Colloquium, 21 Oct 1993.

Rare Decays of B^0 and $B^{\pm}$ Mesons: A Fixed-Target Approach, L.D. Isenhower, Texas Tech University Physics Department Colloquium, Feb. 4, 1993.

Student Participation in the ACU Particle Physics Research Program, M. E. Sadler, Workshop on Teaching Nuclear, Atomic and Surface Physics with Accelerators, University of North Texas, Denton, 31 October 1992.

The New Neutral Meson Spectrometer at LAMPF, (presented in Russian) M. E. Sadler, Petersburg Nuclear Physics Institute, Gatchina, Russia, 23 June 1992.

A Cosmic Ray Tomography System for Testing Scintillation Crystals and a Brief Report on a Fixed-Target Rare B and D Meson Decay Experiment at Fermilab, L.D. Isenhower, Uppsala University, Sweden, June 18, 1992.

Baryon Resonances at PILAC, M. E. Sadler at the Institute for Nuclear Theory, University of Washington, Seattle, 6 January 1992.

A View on High Energy Physics and International Collaborations, L.D. Isenhower, ACU Faculty Scholars' presentation given Oct. 1991 at ACU.

The World's First Complete Measurements in the Pion-Nucleon System, M. E. Sadler, University of Warsaw, Poland, 31 May 1991.