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EXPERIMENTAL STUDIES OF NUCLEON-NUCLEON AND PION-NUCLEUS INTERACTIONS AT INTERMEDIATE ENERGIES

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Contents

1 Introduction

This report summarizes the work on experimental research in intermediate energy nuclear and particle physics carried out by New Mexico State University in 1988–91 under a grant from the U. S. Department of Energy.

Most of these studies have involved investigations of neutron-proton and pion-nucleus interactions. The work has been carried out both at the LAMPF accelerator at the Los Alamos National Laboratory and at the Paul Scherrer Institute (PSI, formerly SIN) near Zurich, Switzerland. It represents a collaborative effort among several laboratories and universities. The NMSU personnel during this period included two faculty members, George R. Burleson and Gary S. Kyle; four postdoctoral research associates, John Faucett, Sanjoy Mukhopadhyay, Andreas Klein, and Mohini Rawool-Sullivan; eight graduate students, Robert Garnett, Mohini Rawool, Michael Beddo (who completed Ph.D. theses during this period), Ming-Hong Wang, Maher El-Ghossain, Qihua Zhao, Kevin Cranston, and James Stevens; and one undergraduate student, Brian Berman.

The neutron-proton research is part of a program of studies of interactions between polarized nucleons that we have been involved with for more than ten years. Its purpose has been to help complete the determination of the full set of ten complex nucleon-nucleon (NN) amplitudes at energies up to 800 MeV, as well as to continue investigating the possibility of the existence of dibaryon resonances. The five complex isospin-one (proton-proton) amplitudes have been fairly well determined, partly as a result of this work. It is expected that additional experiments at LAMPF and other laboratories will complete the data set needed for the first determination of the complex isospin-zero amplitudes (found from neutron-proton scattering) within the next two or three years. Our work in this period has involved measurements and analysis of data on elastic scattering and total cross sections for polarized neutrons on polarized protons.

The pion-nucleus research continues our studies of this interaction in regions where it has not been well explored. One set of experiments includes studies of pion elastic and double-charge-exchange (DCX) scattering at energies between 300 and 550 MeV, where our data are unique. Another involves elastic and single-charge-exchange (SCX) scattering of pions from polarized nuclear targets, a new field of research which will give the first extensive set of information on spin-dependent pion-nucleus amplitudes. Still another involves the first set of detailed studies of the kinematic correlations among particles emitted following pion absorption in nuclei. This used a new detector system, which we helped construct, that covers nearly the full solid-angle region.

2 Experimental Research

2.1 Nucleon-Nucleon Interactions

During this period, we have been involved with the following experiments at LAMPF:

Experiment No. 665/770, *The Measurement of np Elastic Scattering Spin Correlation Parameters with L- and S-Type Polarized Beam and Target between 500 and 800 MeV,* Argonne National Laboratory, Texas A & M University, University of Montana, Washington State University, LANL, and NMSU (Faucett, Rawool, Garnett, Kyle, and Burleson); H. Spinka, Argonne, and G. Burleson, Spokesmen.

This experiment is one of a series of measurements at LAMPF of spin-dependent variables in neutron-proton elastic scattering. It is part of a long-term program at LAMPF that is aimed at determining the five isospin-zero (I=0) amplitudes of the nucleon-nucleon interaction over the LAMPF energy region, up to 800 MeV. While the five isospin-one (I=1) (pp) amplitudes are now fairly well determined up to about 1 GeV,[1] the I=0 amplitudes (contained in the np system, along with the I=1 amplitudes), are very poorly known.[1,2,3,4,5,6] It is important to experimentally determine all the nucleon-nucleon amplitudes, both for comparisons with theoretical calculations of this fundamental process with meson exchange,[7] quark,[8] and Skyrmion models,[8] and for calculations of nucleon-nucleus interactions, which require these amplitudes as inputs.

Experimental studies of pp scattering have suggested the possibility of the existence of broad dibaryon resonances, though they have not been established as yet. Because of the fundamental nature of the nucleon-nucleon interaction, it is important to know whether such resonances exist. The I=0 channel is especially important for this study, since it does not contain amplitudes for $\Delta(1232)$ production, a process that can mimic resonances in the I=1 channel. This has been a very active field of research; a discussion of the history of dibaryon resonances has been given by Locher, *et al.*[9]

The data base for np elastic and inelastic interactions is sparse above 500 MeV.[3] There are a number of np differential cross section and polarization measurements, especially at backward angles, but there are only a few measurements of other spin parameters. In this experiment, measurements were made of the initial spin correlation parameters C_{LL}, C_{SS}, and C_{LS} in np elastic scattering at center-of-mass angles between 36° and 172° at energies of 500, 650, and 800 MeV, with some measurements at other energies, which should significantly increase the data base. The LAMPF polarized neutron beam was used, with a polarized proton target. A spectrometer system consisting of a large-aperture magnet and wire chambers was set up to measure the momentum and angle of the recoil proton, to identify elastic events. Three positions of this spectrometer were used to cover the full angular range.

Experimental running began in fall, 1983, and ended late in 1985, producing about 1000 rolls of magnetic tape containing the events. About two-thirds of the data have been analyzed and compared with phase-shift predictions, as Ph.D. theses of M. Rawool[10] and R. Garnett,[11] NMSU. Some results are shown in Figs. 1 and 2, compared with phase-shift predictions. A study was made with some of these results to determine which partial waves in existing phase-shift solutions will be most sensitive to the new data.[11] This indicated that both spin-singlet and spin-triplet partial waves will be modified, so that it is difficult to predict precisely which amplitudes will be affected, and to what extent. Continuing work on data analysis is in progress by Argonne National Laboratory, and detailed articles describing the results are being prepared. Some of these results have been published.[12,13]

Experiment No. 960, *Measurements of Total Cross Section Difference in Neutron-Proton Scattering for Longitudinally Polarized Beam and Target*, same collaboration as above; H. Spinka, Argonne, L. C. Northcliffe, Texas A & M, and G. Burleson, Spokesmen.

In this experiment, the quantity $\Delta\sigma_L$(np) was measured, which is the difference in total cross sections for longitudinally parallel and antiparallel spins for beam and target nucleons. This quantity is important for phase-shift analyses of NN data, since it is directly sensitive to the spin dependence of inelasticities, unlike most of the other quantities being measured in this program, which involve elastic scattering only.

The method used involved detecting polarized neutrons scattered in the forward direction from a polarized proton target, using a hodoscope of long, thick, scintillation counters located downstream of the target. In order to select neutrons of the primary proton beam energy, time-of-flight methods were used, with the LAMPF bunched beam. Fast time-to-digital converters developed at Argonne gave position information on the particles detected in the neutron counters, which was used to determine the relative total scattering cross sections. Coincidences between the perpendicular counter arrays were also used to give this information, so that two separate determinations of $\Delta\sigma_L$(np) were made. Monitoring was car-

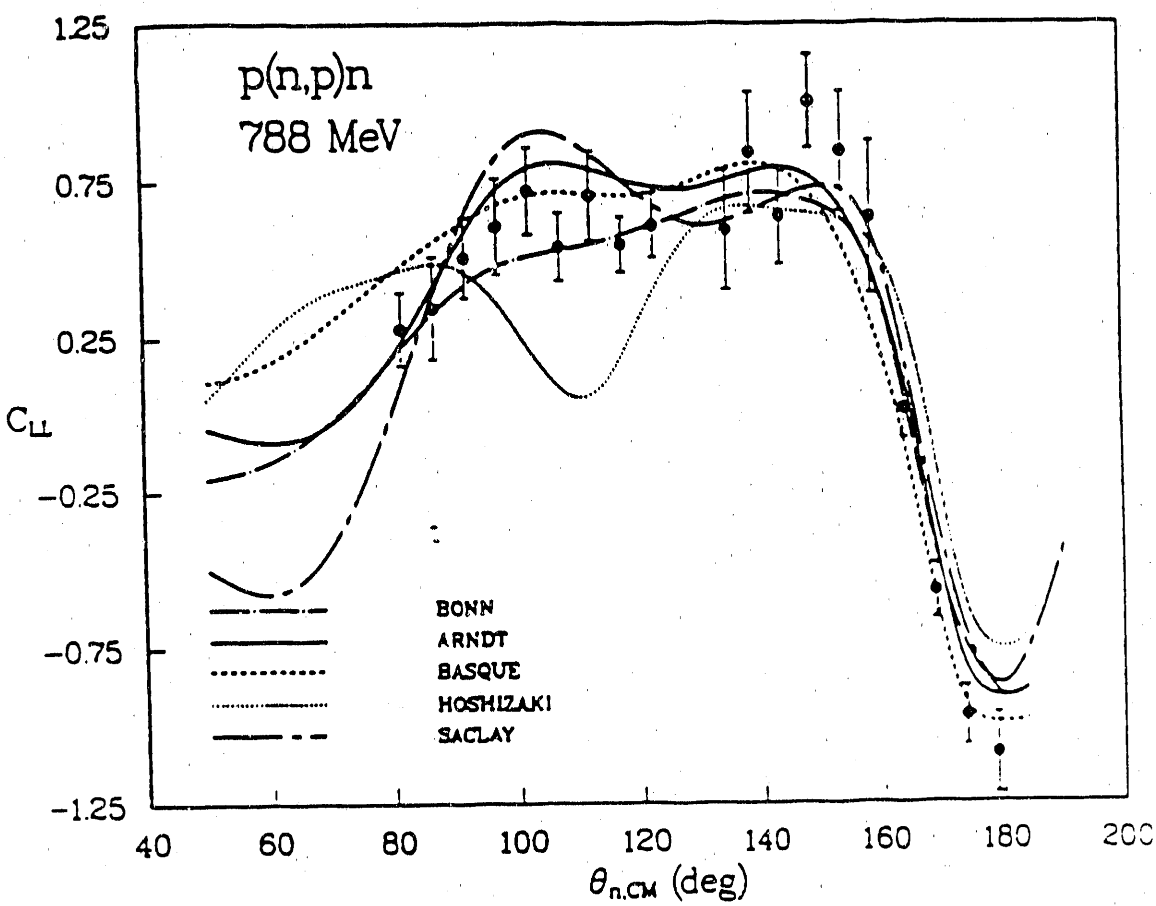

FIG. 1. Experimental values of C_{LL} at 788 MeV, from the thesis of M. Rawool.[10]. The phase-shift predictions shown are from Refs. [6] (Bonn), [1] (Arndt), [4] (Basque), [2] (Hoshizaki), and [3] (Saclay).

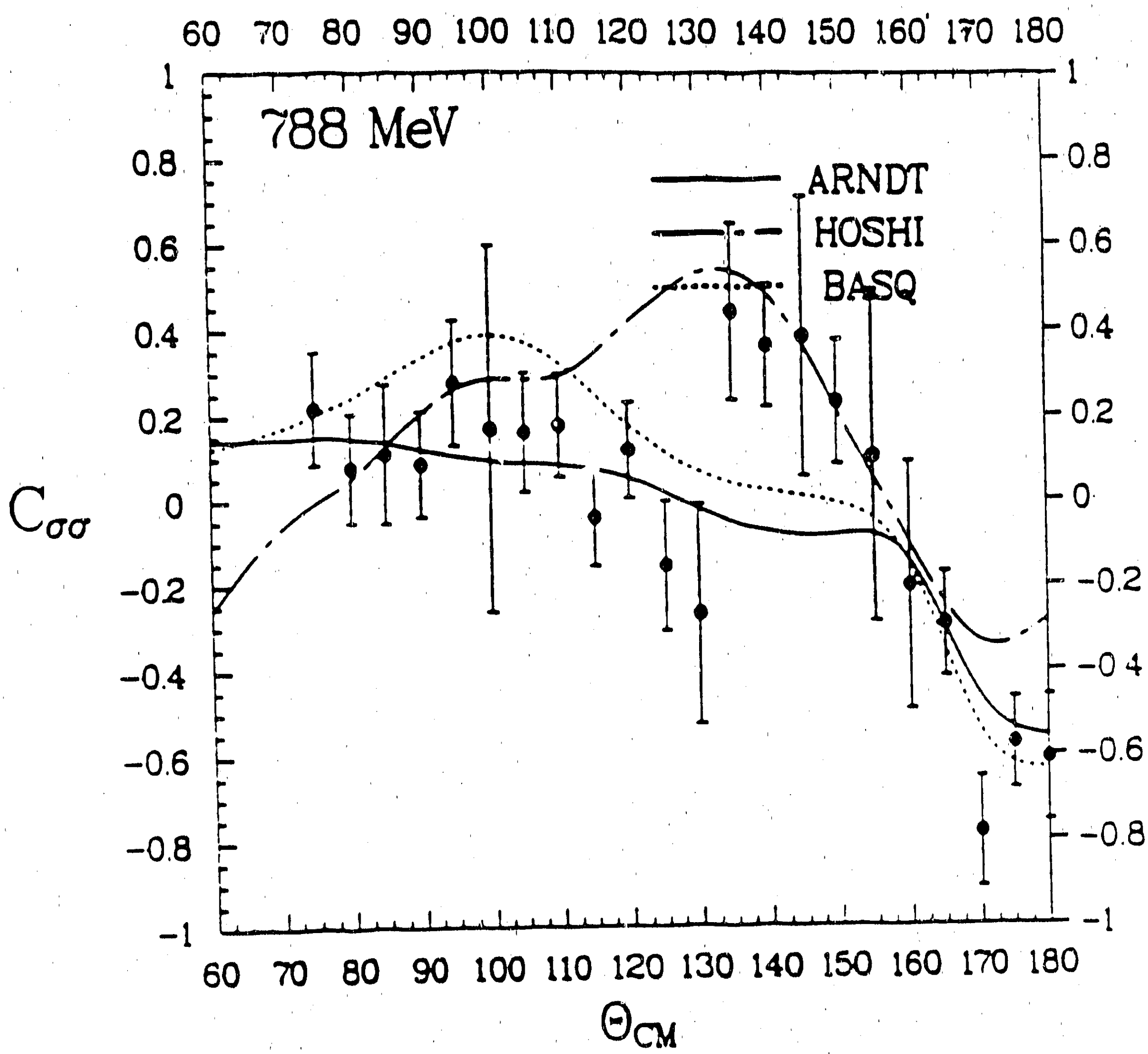

FIG. 2. Experimental values of $C_{\sigma\sigma}$ (nearly the same as C_{SS}) from the thesis of R. Garnett.[11] The phase-shift predictions shown are from Refs. [1] (Arndt), [2] (Hoshizaki), and [4] (Basque).

ried out both in the primary proton beam and in the secondary neutron beam, which was produced by passing the polarized proton beam through a long liquid deuterium target.

The data taking extended over two years and ended in fall, 1988. Measurements of $\Delta\sigma_L$(np) were made at five energies between 500 and 800 MeV. The data analysis was carried out principally by M. Beddo, as a Ph.D. thesis,[14], together with physicists from Argonne. The results for $\Delta\sigma_L$(np) are shown in Fig. 3, together with previous data from Saclay[15], preliminary data from PSI[16] and Saclay,[17] shown with their permission, and earlier data from Argonne[18] extracted from measurements with polarized protons incident on polarized deuterons. The current phase-shift prediction of Arndt[19] is also shown; the poor agreement with the data illustrates the inadequacy of the np data base at these energies. The lack of agreement of the Argonne data with the new results shows that, at least over some energies, the theoretical methods used to extract $\Delta\sigma_L$(np) from $\Delta\sigma_L$(pd) are inadequate.

The results for $\Delta\sigma_L$(I=0) extracted from these data are shown in Fig. 4, compared with the experimental values of $\Delta\sigma_L$(I=1). The similarity in shape suggests a resonantlike behavior in $\Delta\sigma_L$(I=0) as well. Investigations of these data, together with all other np data, by Kroll, using the methods of Grein and Kroll,[20] indicate the possibility of a singlet or triplet resonance with mass about 2200 MeV and width 50–75 MeV. This structure cannot be explained by threshold effects or other nonresonant contributions from the inelastic channel. These results are being prepared for publication.

2.2 Pion-Nucleus Interactions

During this period we have been involved in several experiments in pion-nucleus interactions at LAMPF and PSI. These include the following:

2.2.1 Experiments at LAMPF

At LAMPF we have been involved in two programs of experiments, studies of pion-nucleus elastic and double-charge-exchange scattering at energies above the Δ(1232) resonance, and studies of pion interactions with polarized nuclear targets. The work on the former includes the following experiments:

Experiment No. 1107, *Studies of Pion Double Charge Exchange Scattering at Energies above the Δ Resonance*, University of Texas, University of Pennsylvania, George Washington University, LANL, and NMSU (Faucett, Burleson);

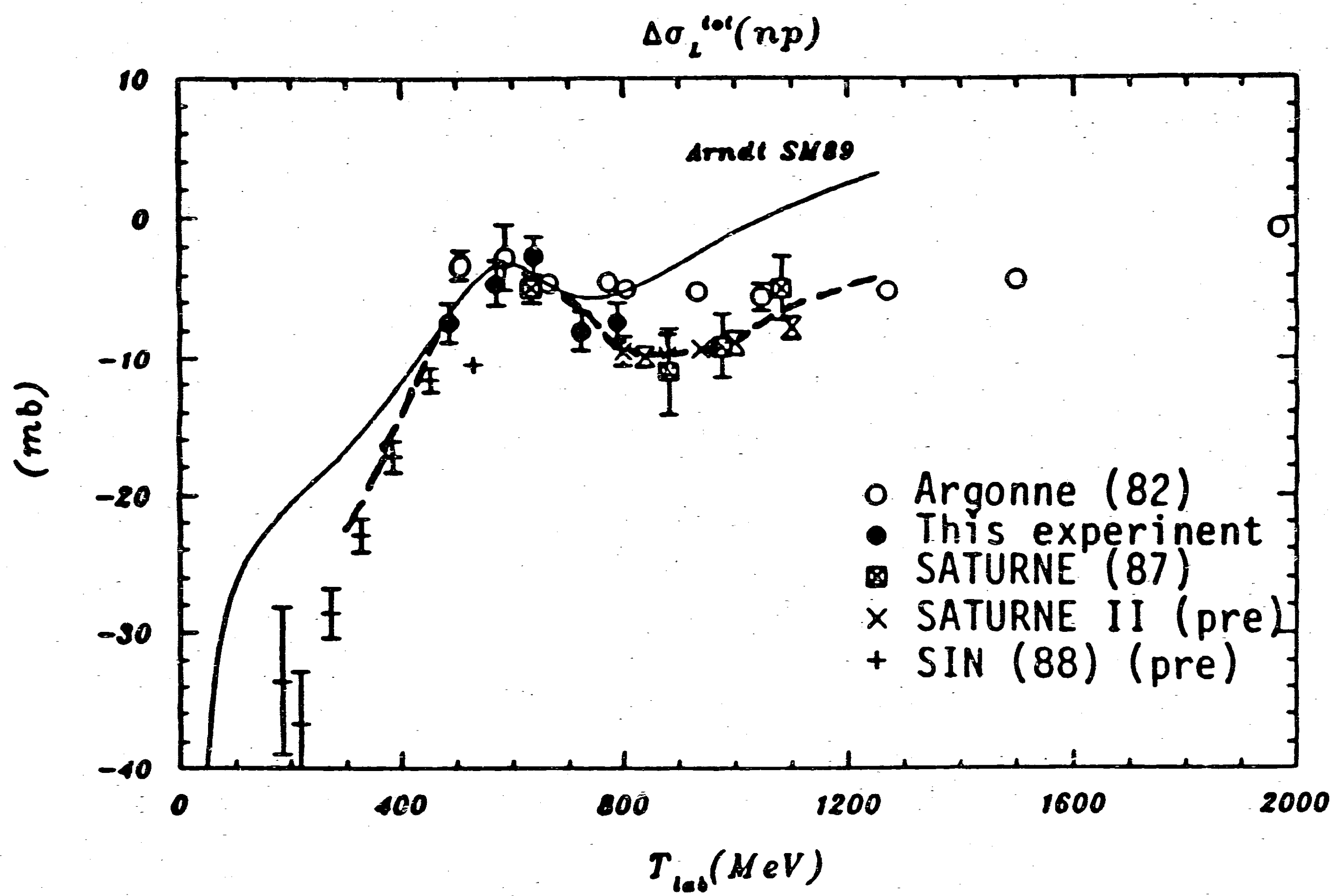

FIG. 3. Experimental values of $\Delta\sigma_L$(np) from Experiment No. 960, together with the published data from Argonne (revised),[18] and SATURNE,[15] and the unpublished data from SATURNE[17] and PSI.[16] The solid curve is the phase-shift prediction of Arndt,[19] and the dashed curve is intended to guide the eye. (Figure taken from the thesis of M. Beddo.[14])

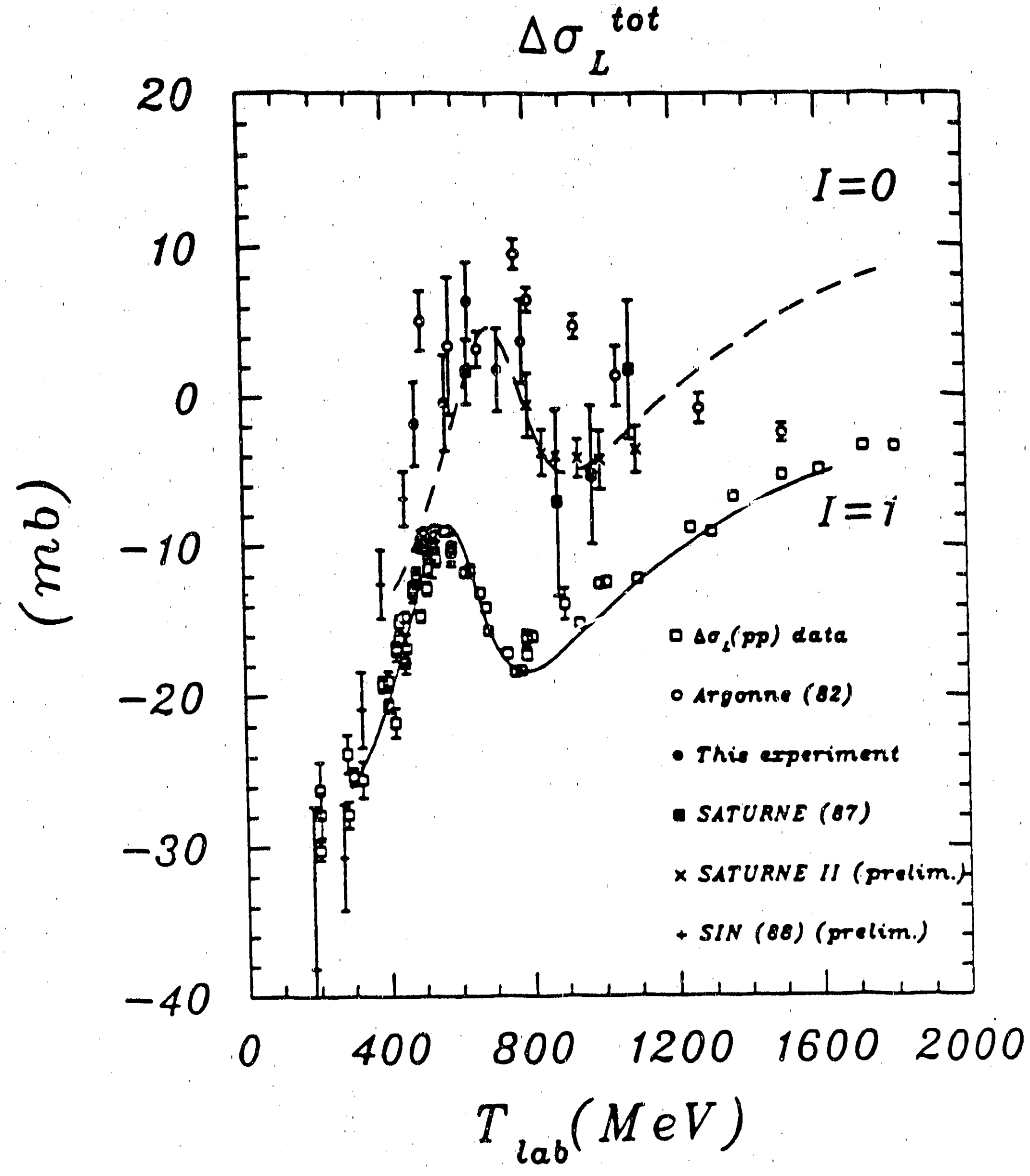

FIG. 4. Experimental values of $\Delta\sigma_L$(I=0) and $\Delta\sigma_L$(I=1). The labelling of points on the I=0 curve are the same as in Fig. 3. The dashed curve is meant to guide the eye. It is identical in shape to the I=1 curve, but displaced along the horizontal and vertical axis. (Figure taken from the thesis of M. Beddo.[14])

G. Burleson, Spokesman; and **Experiment No. 1106**, *Studies of Pion-Nucleus Elastic Scattering at Energies above the Δ Resonance*, same collaboration as above; K. S. Dhuga, GWU, and J. A. McGill, LANL, Spokesmen.

These experiments are continuations of work begun by this collaboration in 1987, which obtained the first extensive set of measurements of pion interactions at energies immediately above the Δ(1232) resonance. For this work, the P^3 Channel at LAMPF was modified in order to produce a dispersed beam spot, with a dispersion of 2 cm per percent $\Delta p/p$. The Large Aperture Spectrometer (LAS) was also modified to improve its resolution. Changes included installing new drift chambers to give better spatial resolution, a sweeping magnet located before the spectrometer to remove beam pions in order to allow clean detection of pions of opposite charge, a vacuum scattering chamber and a helium bag to reduce multiple scattering, and a gas threshold Cherenkov counter (designed by our group) to veto electrons. These improvements resulted in a resolution of about 1.5–2.0 MeV at energies between 300 and 500 MeV.

The principal motivation for this work is based on the observation that the pion-nucleon interaction is considerably weaker at these energies than near the peak of the Δ resonance. This means that the resulting longer mean free paths for pions in nuclei and the weaker optical potentials should lead to more reliable theoretical calculations. These energies also have advantages over those below the resonance, where second-order effects are larger.

DCX scattering is of particular interest because it must take place on at least two nucleons and therefore should have the possibility of giving new insights into nucleon-nucleon correlations. In order to carry out detailed calculations of DCX at these energies, however, it is necessary to know how well models of the pion-nucleus interaction can reproduce simpler interactions, such as elastic scattering. Partly for this reason, measurements were carried out on both of these processes.

The elastic-scattering measurements were made at 400 and 500 MeV, for both $\pi^{\pm}$. The angular range extended to $\sim 50°$ for π^+ and $\sim 40°$ for π^-, and the targets included ^{12}C, ^{40}Ca, ^{90}Zr, and ^{208}Pb. The data were analyzed principally by George Kahrimanis, of the University of Texas, as an M.S. thesis. Some results for ^{40}Ca and ^{208}Pb are shown in Figs. 5 and 6. Preliminary comparisons with a first-order relativistic field-theoretic optical model show good agreement if the size of nucleons in the nucleus are reduced somewhat over their free values.[21] These results are being prepared for publication.

Fig. 7 shows our published results[22] on small-angle excitation functions for transitions to double isobaric analog states (DIAS) in ^{14}C and ^{18}O, with some previous measurements of single-charge-exchange scattering (SCX),[23] compared

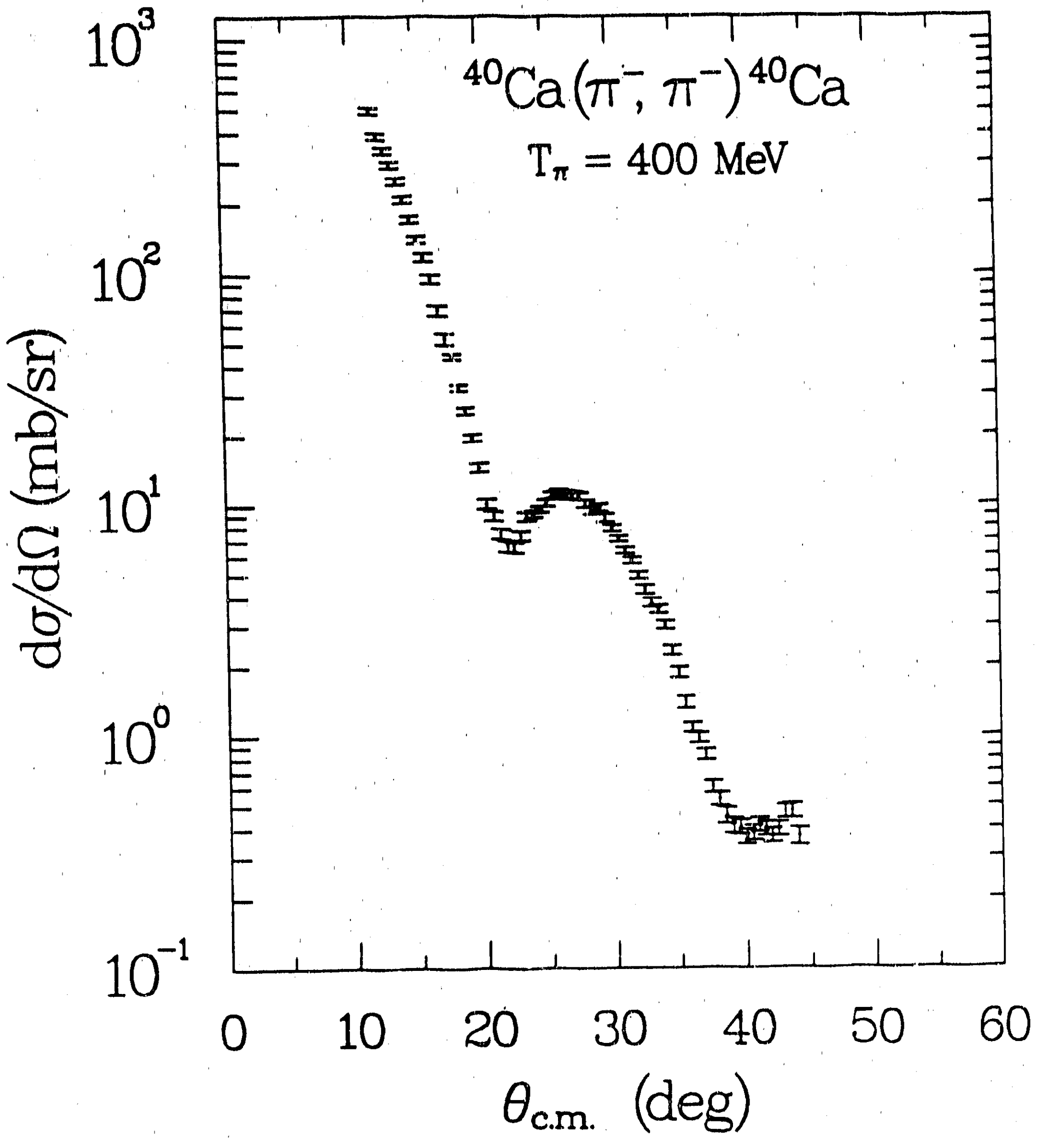

FIG. 5. Experimental angular distribution for π^- scattering on ^{40}Ca at 400 MeV, from Experiment No. 1106.

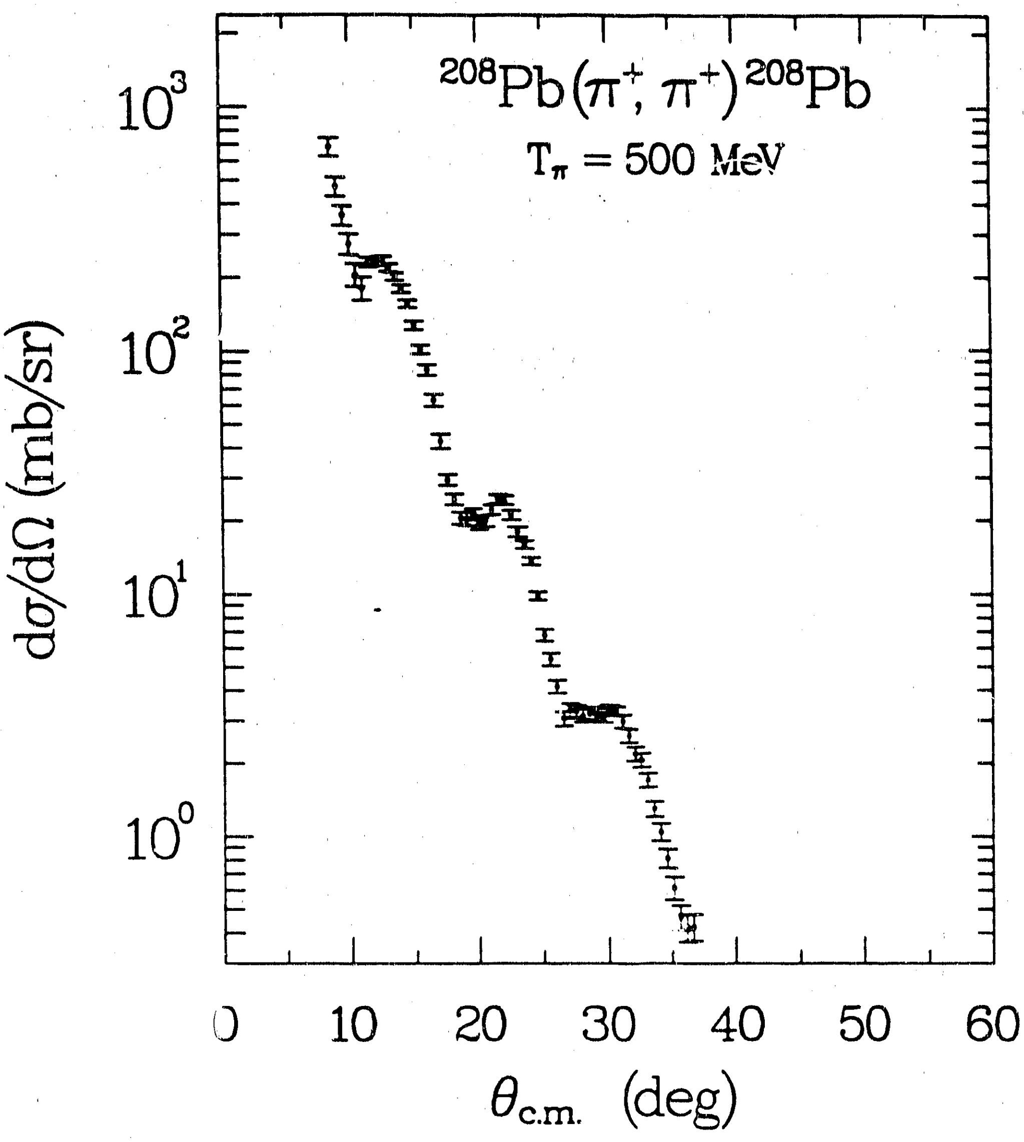

FIG. 6. Experimental angular distribution for π^+ scattering on ^{208}Pb at 500 MeV, from Experiment No. 1106.

with several predictions. One of these is the six-quark cluster model of Miller,[24] which predicts a peak that is not observed. Another is due to Parnell and Ernst,[25] based on a first-order optical model with no free parameters which is consistent with the SCX data but is about a factor of three too small for the DCX results. Another predictı is due to Haider and Liu,[26] which is consistent with the data. This is a distorted-wave calculation, made in the context of the possibility of a bound state of an η^o in a nucleus, the signature of which is indicated by the wiggle in the curve.

Measurements were also made of small-angle cross sections and excitation functions for several other nuclei, including some in the $f_{7/2}$-shell. The latter were compared with the predictions of a two-amplitude model[27] which describes DCX scattering in terms of transitions through analog states (involving long-range effects) and nonanalog states (involving short-range effects, including NN correlations). This model had described both analog and ground-state transitions very well at lower energies.[27,28,29]

In our data, we find two problems with fits to this model. One is that the experimental cross sections for transitions to all the nonanalog ground states are considerably smaller than predicted by a fit to the analog transitions in ^{42,44,48}Ca, ^{50}Ti, and ^{52}Cr, as shown in Fig. 8 for ^{44}Ca. The other is that the experimental cross sections to the analog states of the isospin-one nuclei ^{46}Ti and ^{54}Fe are also considerably smaller than predicted by this fit, as shown in Fig. 9. The indication is that this model needs further study. Some of these results have been submitted for publication. This work should serve as the basis of a Ph.D. thesis for Allen Williams, of the University of Texas.

Our work on pion interactions with polarized nuclear targets includes the following experiments, which are the first measurements at LAMPF of the scattering of pions from a polarized nuclear target:

Experiment No. 1023, *Analyzing Power Measurements for the (π^+, π^0) Reaction on a Polarized ^{13}C Target,* Arizona State University, University of Minnesota, University of Texas, University of Maryland, University of Colorado, LANL, and NMSU (Kyle, Klein, Cranston, Burman, and Burleson); J. Comfort, ASU, and G. Kyle, Spokesmen.

Studies of pion-nucleus interactions have concentrated on attempting to describe the reaction mechanism, finding new information on nuclear structure, and investigating the modification the pion-nucleon interaction in the nuclear medium, including the formation of the Δ resonance. The pion-nucleus interaction consists

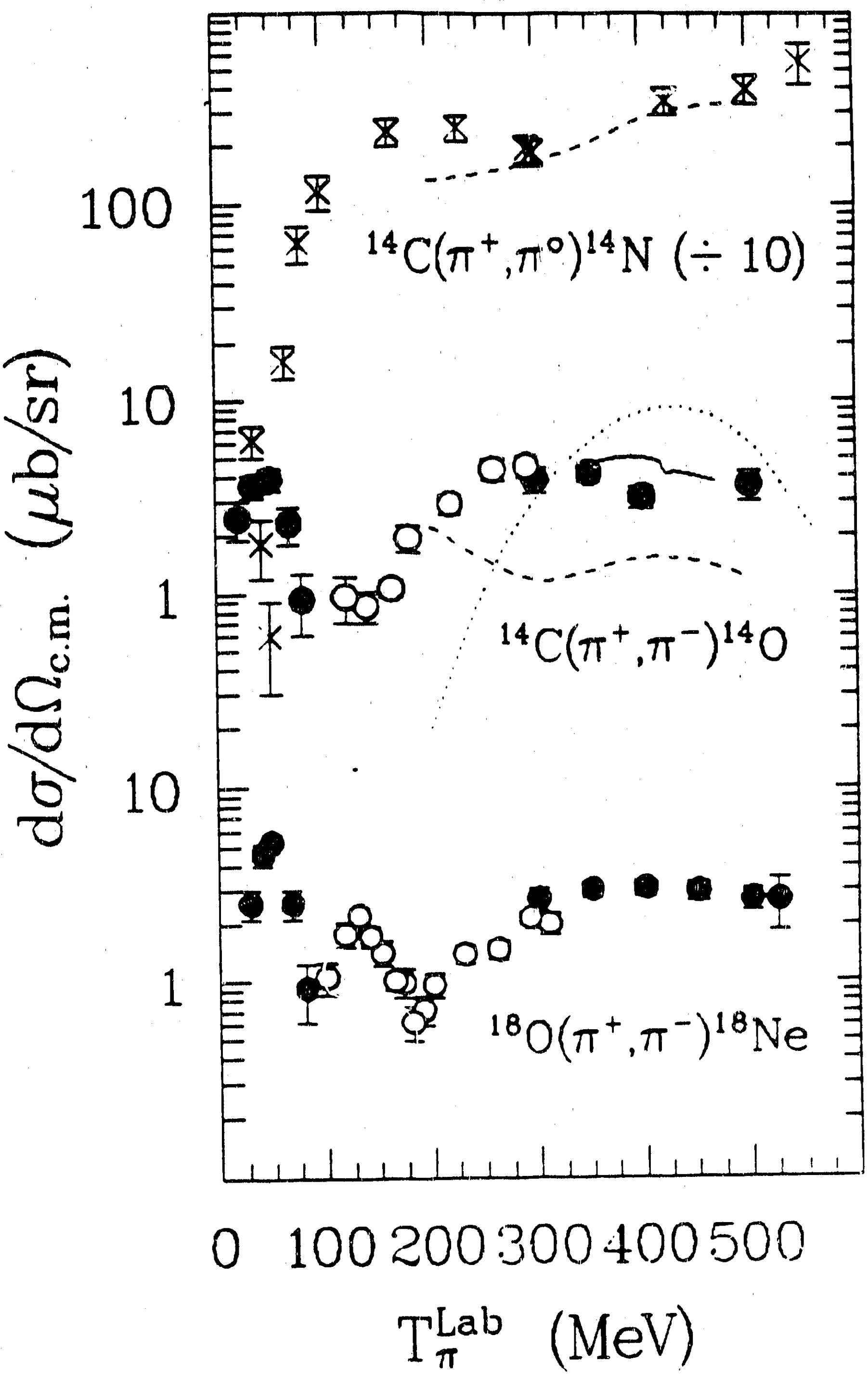

FIG. 7. Small-angle cross sections for SCX scattering to analog states from ^{14}C (crosses) and for DCX scattering to analog states from ^{14}C and ^{18}O (closed circles, from this work; open circles, previous data). The theoretical curves are from Ref. [24] (dotted curve), Ref. [25] (dashed curve), and Ref. [26] (solid curve).

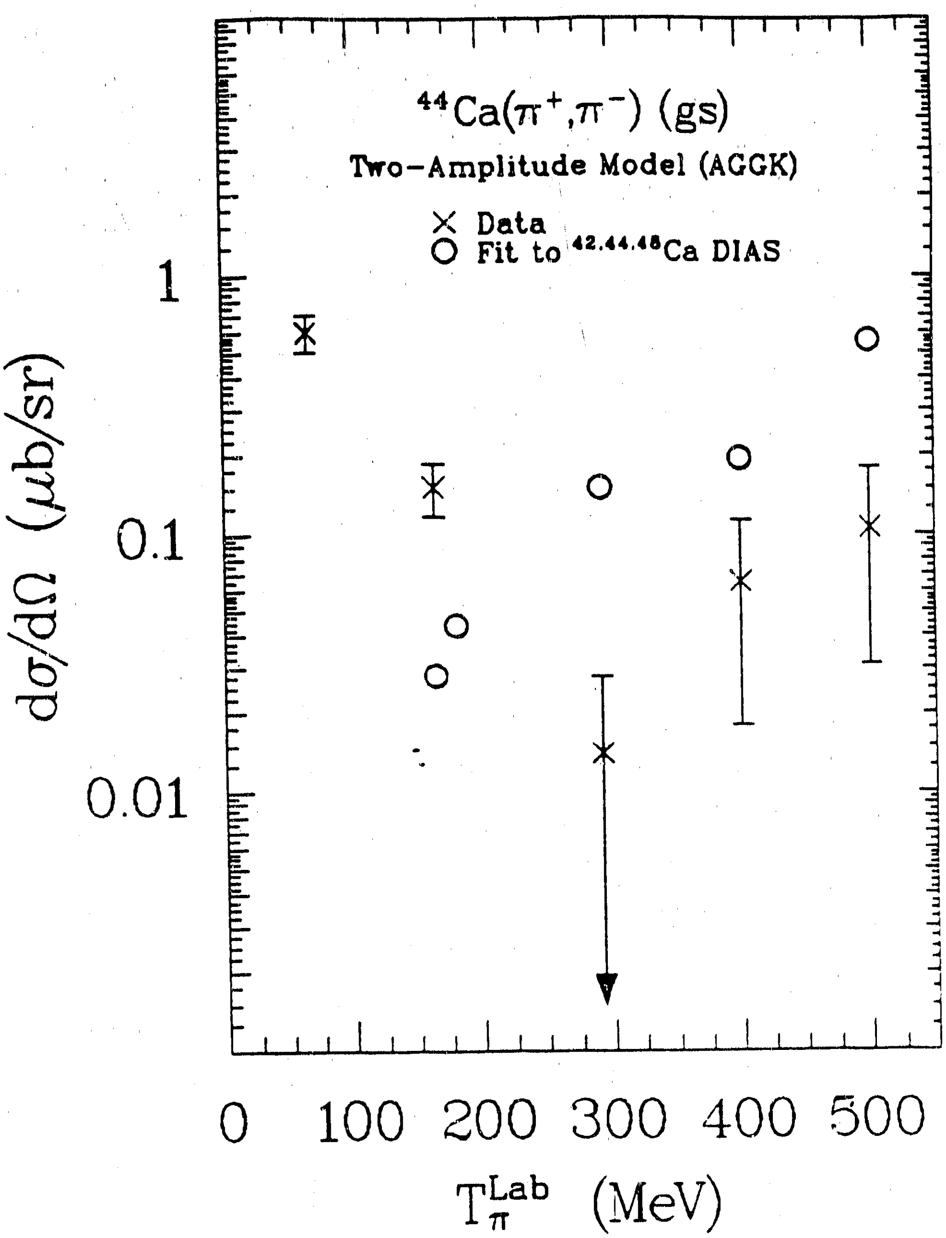

FIG. 8. Predictions of ground-state cross sections for DCX transitions in ^{44}Ca as a function of energy, from fits to DCX analog transitions in ^{42,44,48}Ca (open circles) of the model of Ref. [27]. The experimental values of these cross sections are shown by the crosses. Those for pion energies $\geq$ 300 MeV are from this work and the others are from previous measurements.

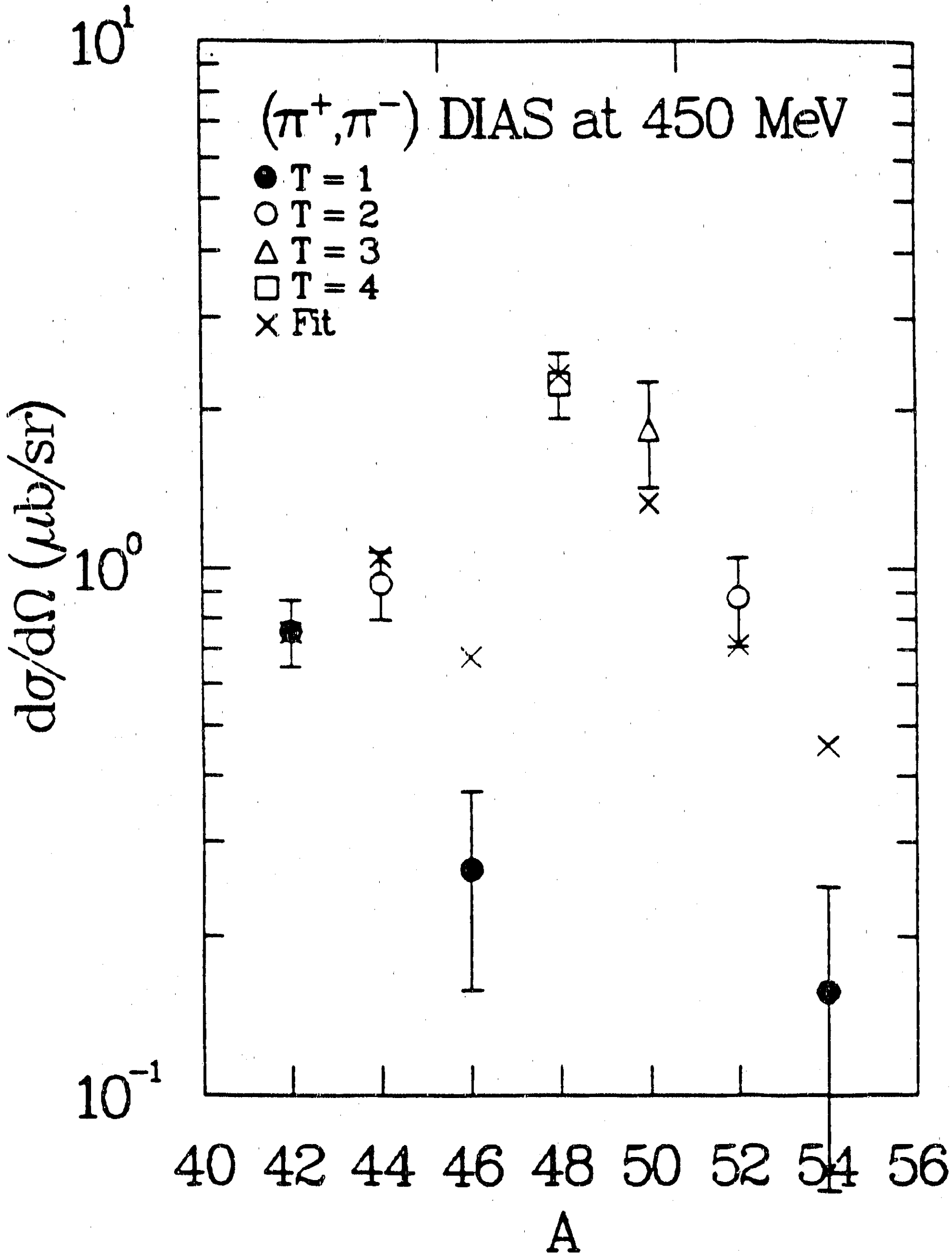

FIG. 9. Results of a fit of cross sections for DCX analog transitions in the $f_{7/2}$-shell nuclei ^{42,44,48}Ca, ^{50}Ti, and ^{52}Cr at 450 MeV to the model of Ref. [27], as a function of nuclear number A (crosses). Also shown are predictions of cross sections for ^{46}Ti and ^{54}Fe (crosses). The experimental data, from this work, are shown with the symbols indicated for different values of the isospin T.

both of spin-independent and spin-dependent parts, but the experimental data so far have been sensitive principally to the spin-independent amplitudes, so that little is known about the spin-dependent ones. Differential cross sections are represented by the sums of squares of amplitudes, so that the smaller spin-dependent amplitudes generally make small contributions to them. The asymmetry of pions scattered from polarized nuclei, however, is represented by the interference between spin-independent and spin-dependent amplitudes, so that the effects of the smaller amplitudes are magnified. These measurements should also be sensitive, in particular, to the strength of the Δ-nucleus spin-orbit interaction. Different calculations of pion-nucleus scattering involving the delta-hole model, for example, use a Δ-nucleus spin-orbit interaction that is strong,[30] weak,[31], or zero.[32]

Interest was originally stimulated in these studies by a workshop at LAMPF in 1986,[33] which reported a number of theoretical studies, nearly all of which predicted large effects. Partly in preparation for this work, we were involved in the first experiment at LAMPF that used a polarized nuclear target, which was run in 1988. This was **Experiment No. 955**, *Polarized Proton Scattering from Polarized Nuclear Targets*, University of Texas, Arizona State University, University of Minnesota, LANL, and NMSU; G. W. Hoffmann, R. L. Ray, and M. L. Barlett, Texas, and J. Jarmer, LANL, Spokesmen. In this experiment, polarized 500-MeV protons were scattered from a polarized ^{13}C target, and the elastic scattering spin observables A_{ooon} (target analyzing power) and A_{oonn} (beam-target spin correlation parameter) were determined over the angular range of 10^o – 30^o. The data were analyzed at the University of Texas, and the results are shown in Fig. 10. The experimental points indicate smooth angular distributions, with structure in the regions of the minima of the differential cross sections. Predictions of distorted-wave Born approximation calculations,[34] using either the relativistic or nonrelativistic impulse approximation, are in reasonable agreement with these data. The results have been submitted for publication.

Experiment No. 1023, together with the following one, ran for about five months in the Low Energy Pion Channel in 1989. The same target setup was used for both, but the detector systems used were different. In this experiment, measurements were made of the asymmetry of SCX scattering from polarized ^{13}C, which was in the form of ethylene glycol ($C_2H_6O_2$, enriched to 99% ^{13}C). The ^{13}C nuclei were polarized to about 28% and the H nuclei to about 80% by microwave irradiation at low temperature (0.5 K) in a large magnetic field (2.5 T). The pion energy was 164 MeV, and the angular range extended between 25^0 and 65^0, covering the region where cross-section data exist and where a minimum in the angular distribution is seen. The LAMPF pi-zero spectrometer system was used to detect

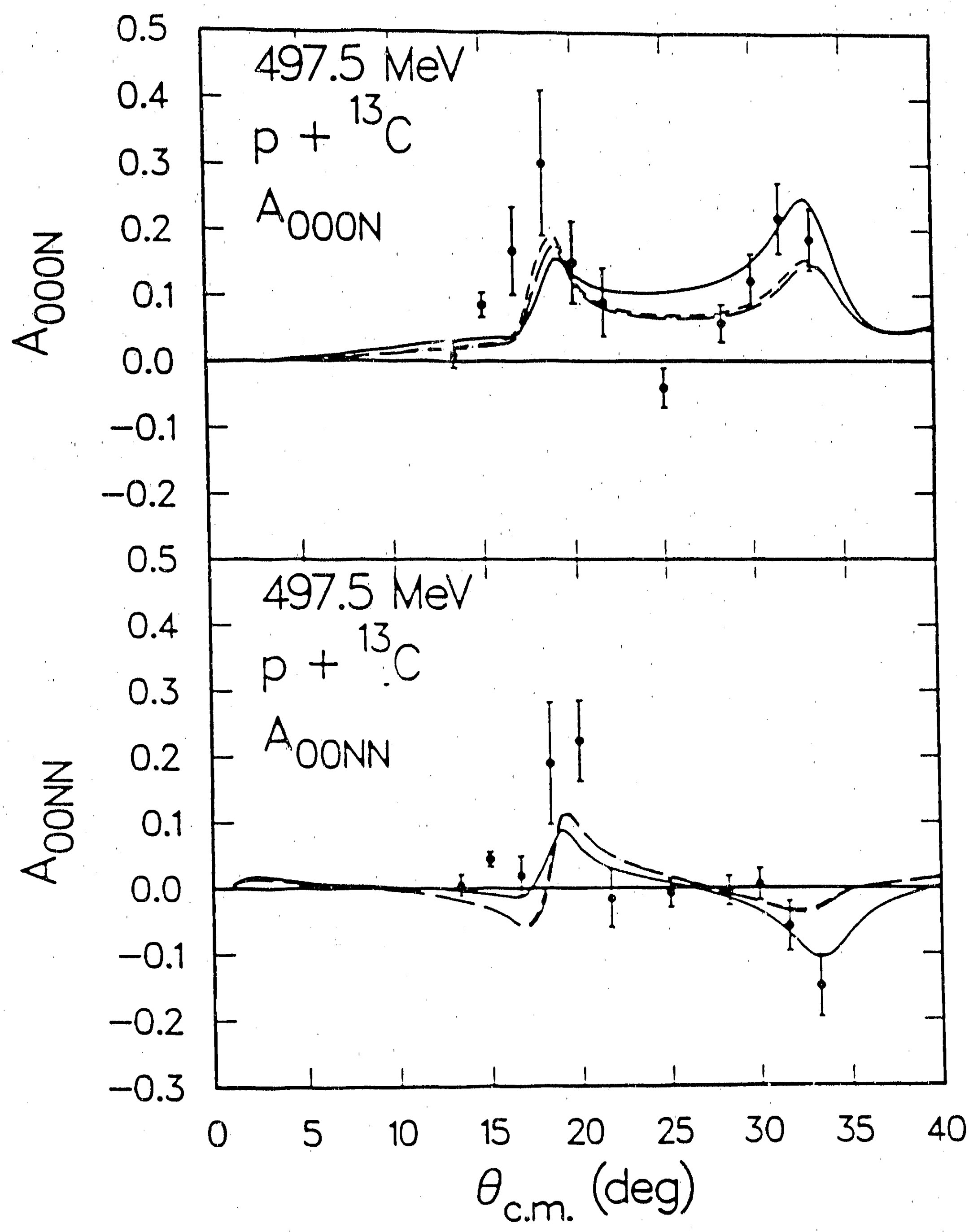

FIG. 10. Experimental data and theoretical predictions for the spin observables A_{ooon} and A_{oonn} for polarized protons scattered from polarized ^{13}C at 500 MeV, from Experiment No. 955. The solid (dashed) curves show predictions of a relativistic impulse approximation calculation assuming relativistic (nonrelativistic) values for the lower-component wave function of the valence neutron. The nonrelativistic predictions are given by the dash-dotted curve.

the π^0's, and runs with dummy targets were used to correct for background effects. Measurements were also made of the $\pi^- p$ charge exchange asymmetry, with the results shown in Fig. 11, which agree well with the predictions of the Arndt phase shifts.[19]

The π^0 spectra from ^{13}C were fitted with three peaks, since the assumption of a single peak did not give a good representation of the spectra or correctly reproduce the recoil kinematics. These corresponded to the isobaric analog state (IAS) of the residual ^{13}N nucleus, the pair of $3/2^-$ and $5/2^+$ excited states at 3.5 MeV, and a group of states at 7.5-MeV excitation. The experimental cross sections and asymmetries for the ground state and the 3.5-MeV state are shown in Fig. 12, compared to two distorted-wave impulse-approximation calculations. The coordinate-space calculation of Siegel and Gibbs[35] reproduces the observed IAS cross section very well and follows the trend of the analyzing-power data at forward angles, but disagrees at the larger angles. The momentum-space calculation of Chakravarti[36] gives cross sections that are too low by a factor of about 2.5, and its asymmetry prediction disagrees with the data over most of the angular range. Both have difficulty in describing the excited-state data, although the $5/2^+$ transition has not yet been included. The principal difference in these two calculations at present is the treatment of medium modifications to the distorted waves, in that they are included in the calculation of Siegel and Gibbs, but not in that of Chakravarti. These results have been submitted for publication. This work will be the basis of a Ph.D. thesis of Joseph Görgen, of Arizona State University.

Experiment No. 1025U, *Pion Elastic Scattering from Polarized* ^{13}C, University of Minnesota, Arizona State University, University of Texas, University of Pennsylvania, and NMSU (Burleson, Klein, Cranston, Burman, and Kyle); D. Dehnhard, Minnesota, and G. Burleson, Spokesmen.

This experiment used the same target setup as Exp. 1023, but with a different detector system, the Large-Aperture Spectrometer (LAS). While the combined resolution of the channel and spectrometer were not suitable for inelastic scattering studies, it was adequate for measurements of elastic scattering. The target material was butanol ($C_4H_{10}O$), which gave a smaller background from oxygen than ethylene glycol. The polarizations of ^{13}C and H were about the same as obtained for ethylene glycol. Measurements were made of the asymmetry for $\pi^{\pm}$ scattering from ^{13}C at 132 MeV between 35^0 and 125^0 and at 226 MeV between 40^0 and 80^0 (which covered about the same region of momentum transfer as at 132 MeV). In addition, we measured an asymmetry for π^- scattering at a momentum transfer corresponding to the region of a minimum in the scattering cross

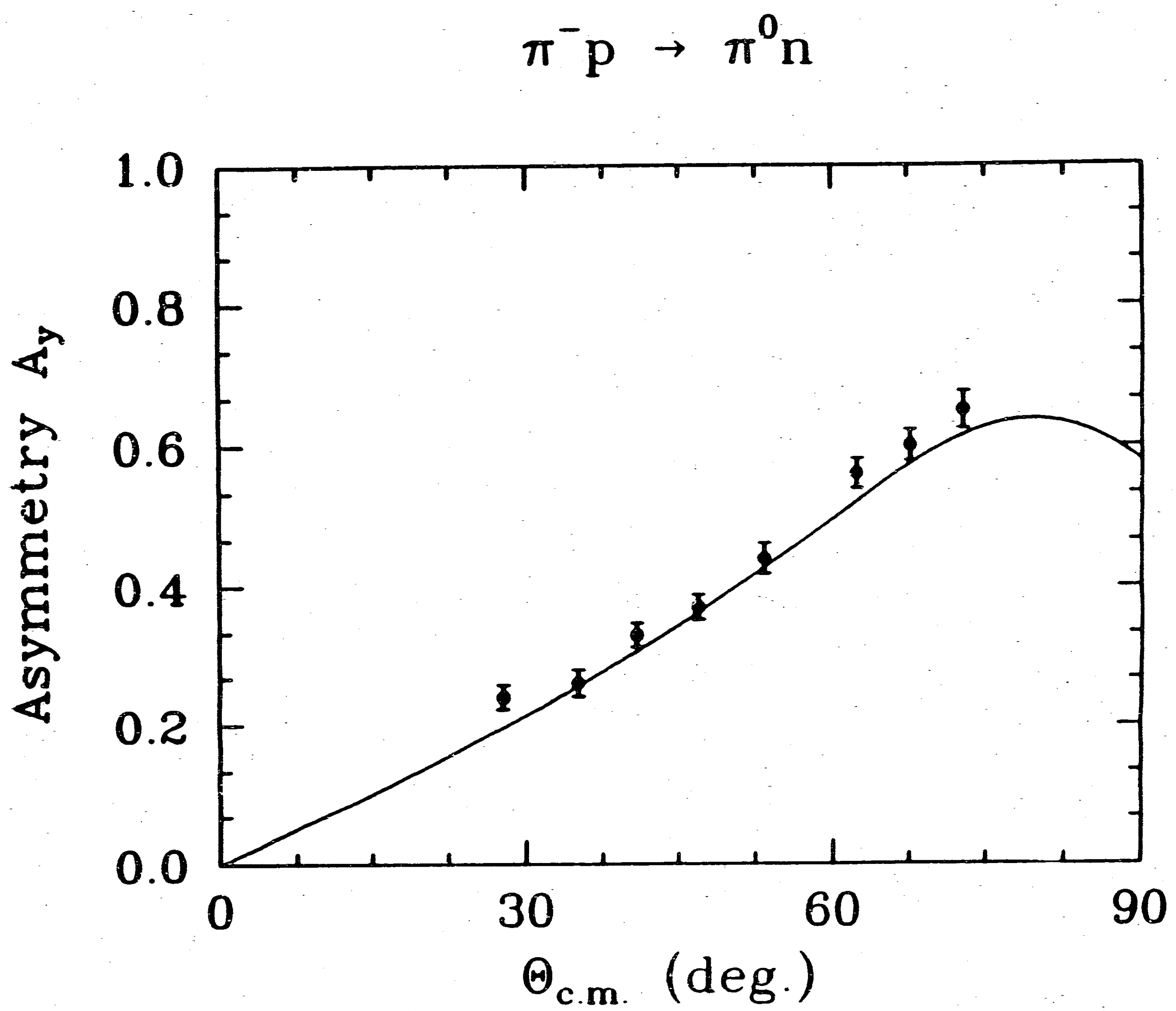

FIG. 11. Experimental values of the asymmetry A_y for $\pi^- \vec{p} \rightarrow \pi^0 n$ at $T_{\pi^-} =$ 161 MeV, from Experiment No. 1023. The line represents prediction of the current phase-shift solution of Arndt.[19] The error bars do not include the target polarization uncertainty of 3.9%.

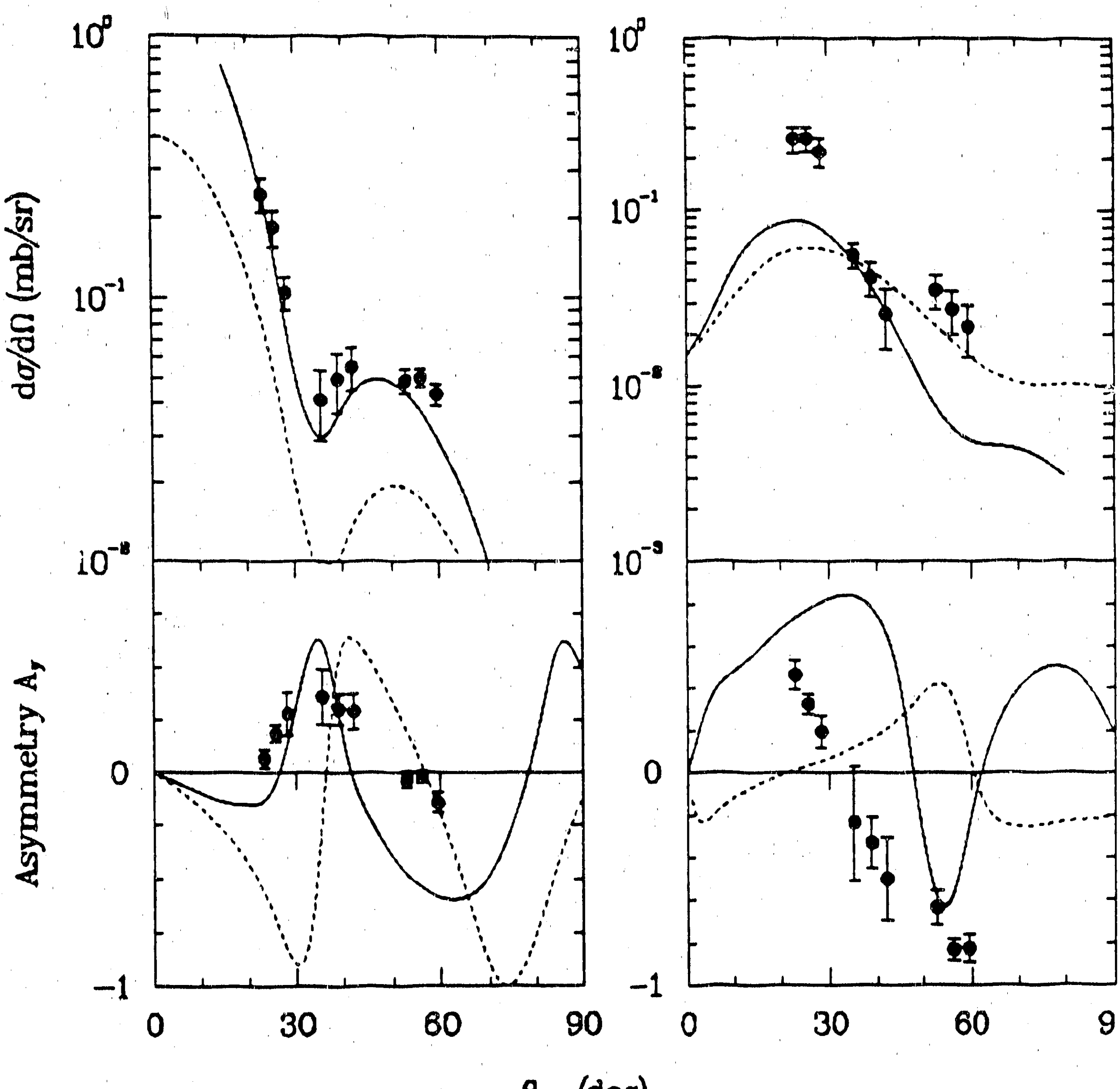

FIG. 12. Cross sections and asymmetries for the $^{13}\vec{C}(\pi^+,\pi^0)$ reaction at 163 MeV, from Experiment No. 1023; (a) IAS transition, (b) transitions to the $3/2^-$,$5/2^+$ doublet at 3.5 MeV. The solid curves represent the calculations of Siegel and Gibbs,[35] and the dashed lines represent those of Chakravarti.[36]

section (where the asymmetry is expected to be a maximum) for energies between 114 and 180 MeV. Measurements were also made of the asymmetry for π^+p scattering at small angles at 132 and 226 MeV, and again the results are consistent with predictions of phase-shift calculations.[19]

The measured asymmetries are small or zero at all energies and angles; the largest values are for π^- at 132 MeV. This behavior is consistent with the zero asymmetry found recently for ^{15}N with 164-MeV π^+ at PSI.[37] The results at 132 and 226 MeV are shown in Fig. 13. The curves represent predictions of the DWIA calculation of Chakravarti[36] and of a first-order optical model with a phenomenological ρ^2 term by Mach and Kamalov.[38] The Chakravarti calculation uses the Cohen-Kurath[39] wave functions, and the Mach calculation uses both the Cohen-Kurath and the Tiator[40] wave functions. It is interesting to note that the Cohen-Kurath wave functions used in two different models give similar results, while the Tiator wave functions give different predictions. None of these gives a satisfactory representation of the full set of data, however. Perhaps the best prediction is that of the Delta-hole model,[41] for which a calculation is available only for π^- at the higher energy. These results have been submitted for publication. This work will be the basis of a Ph.D. thesis of Yi-Fen Yen, of the University of Minnesota.

Experiment No. 1025, *Pion Elastic and Inelastic Scattering from Polarized ^{13}C*, same collaboration as above.

This experiment was carried out in summer, 1990, using the EPICS system. Several modifications of the EPICS setup were required for this work, including the fabrication of a new section of the incoming beam pipe and a new ion chamber, which were made at NMSU. The target setup was essentially the same as was used in the LEP channel, but the target material was ^{13}C-enriched toluene. Measurements were made of $\pi^\pm$ elastic and inelastic scattering from ^{13}C at 162 MeV, over an angular range from 30° to 90°. The elastic data will supplement the data at lower and higher energies taken in Experiment No. 1025U, which, together with 100-MeV data from TRIUMF,[42] will give a fairly complete measurement of pion asymmetries from ^{13}C over the Δ resonance. This energy was chosen because the differential cross sections for $\pi^\pm$ elastic and inelastic scattering have been measured at this energy.[43] Since the inelastic peaks are expected to overlap each other, these cross sections will be used as a constraint in extracting the asymmetries. They will also be needed for comparison with theoretical calculations, some of which have already been made.[36] A resolution of about 1 MeV was achieved, which should be sufficient to give asymmetry data on a number of

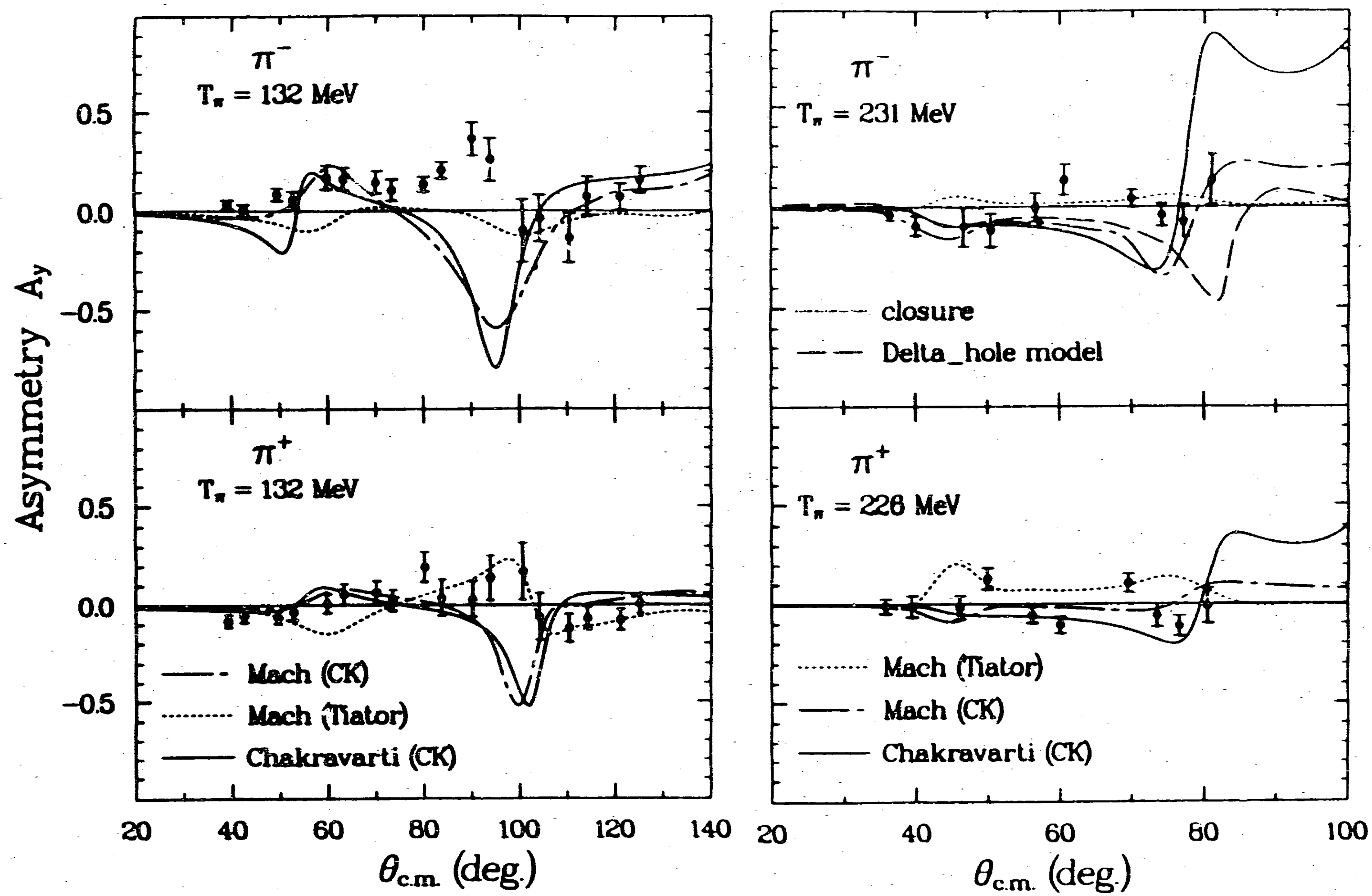

FIG. 13. Asymmetries for elastic scattering of $\pi^\pm$ from $^{13}\vec{C}$ at energies below (left) and above (right) the $\Delta(3,3)$ resonance. The lines represent the calculations of Chakravarti[36] (solid); Mach,[38] using the Tiator wave functions[40] (dashed); Mach,[38] using Cohen-Kurath wave functions[39] (chaindashed); Thies,[41] using the full Delta-hole model (dotted); and Thies,[41], using the Delta-hole model in the closure approximation (chaindotted).

excited states; this will be the first measurement of asymmetries of several excited states of a single nucleus. The data are currently being analyzed, principally by Kevin Johnson, of the University of Texas, who is expected to base a Ph.D. thesis on these results.

Experiment No. 1172, *Cross Sections and Analyzing Power Measurements for $^7Li(\pi, \pi p)^6He$ with Good Kinematic Resolution*, Old Dominion University, University of Maryland, University of Minnesota, Arizona State, University of Texas, University of Pennsylvania, University of Colorado, Universität Karlsruhe, TRIUMF, LAMPF, and NMSU; N. Chant, Maryland, and A. Klein, Old Dominion, Spokesmen.

This experiment was scheduled to run in 1990, with the polarized target setup at EPICS used for Experiment No. 1025, but it was postponed because of difficulty in obtaining suitable polarizable ^{7}LiH target material from Saclay, where the needed irradiation was carried out. Work is in progress to carry out the irradiation locally, and we expect to run the experiment in 1991. We have obtained the NaI(Tl) counters needed for proton detection, as described below, and tested them in the fringe field of the polarized target magnet.

We plan to measure cross sections and analyzing powers for several discrete transitions in the reaction $^7\mathrm{Li}(\pi^+, \pi^+ p)^6\mathrm{He}$. The scattered pions will be analyzed with the EPICS spectrometer, and the protons will be detected and their energies measured with NaI(Tl) counters. Measurements will be made at 240 MeV at pion angles of 60^0, 85^0, and 110^0, with coincident proton angles roughly centered about the quasifree kinematics.

The point of this experiment is to study the two different types of asymmetries that arise from pion-proton quasielastic scattering. One of these is the intrinsic pion-nucleon asymmetry, as modified by the nuclear medium. The other arises from the relatively strong optical absorption of the pion, compared to the proton, which localizes the the reaction on one side of the polarized nucleus. This is known at Newn's polarization, and it has been discussed in the context of pion-nucleus scattering by Gibbs and Siegel.[44] According to calculations of Roos and Chant,[45] it should be possible to separate these effects in an experiment of this kind, since forward scattering should contain strong contributions from the spin dependence of πp scattering and backward scattering relatively little. These results may help shed light on the unexpectedly small asymmetries observed in elastic scattering on ^{13}C and ^{15}N, and they may also be sensitive to the strength of the delta-nucleus spin-orbit interaction, described above.

Experiment No. 1178, *Polarization Asymmetry for the $p(\pi^-,\pi^0)n$ Reaction between 45 and 190 MeV,* same collaboration as Experiment No. 1023; J. Comfort, ASU, and G. Burleson, Spokesmen.

This proposal was presented to the LAMPF Program Advisory Committee (PAC) at its August, 1989, meeting, where it was approved with high rating. It will require the use of a new Neutral Meson Spectrometer (NMS), which is now under development at LAMPF. This device will be similar to the Pi-Zero Spectrometer that was used to detect neutral pions in Experiment No. 1023, but it will have an improved resolution and a larger solid angle. In its report, the pion subcommittee of the PAC noted that it was "most excited about the low-energy proposal. Because of the existing interest in this topic it will put some pressure on designers of the NMS to complete the design expeditiously."

This experiment will explore the πp reaction in two energy regions, that of the Δ resonance and at low energies. At the higher energies, we note that recent measurements at TRIUMF[46] of asymmetries for $\pi^{\pm}\vec{p}$ scattering resulted in reducing considerably the uncertainties in the phase shifts in the Δ region and led to modifying them somewhat. The lowest energy for which asymmetries in πp charge exchange scattering have been measured is 192 MeV,[47] and that we feel that the additional measurements proposed here will improve the situation still further.

At the lower energies the physics interest is different. The chiral bag model of the nucleon, for example, provides a structure to the nucleon that is based on couplings to a pion cloud.[48] A measure of chiral-symmetry breaking in quantum chromodynamics (QCD) via a quark mass term is provided by the so-called sigma term. This term has been calculated in perturbation theory, with an estimate of $\sim$ 35 MeV,[49], which is significantly lower that a recent phenomenological value of $\sim$ 60 MeV deduced from pion-nucleon scattering data.[50] It has been suggested that a large strange-quark component of the nucleon could account for the discrepancy.[51] Studies we have made with the phase-shift code SAID[19] indicate that measurements of asymmetries in πp charge-exchange scattering at energies around 50 MeV, as proposed here, could have significant effects on these results.

2.2.2 Experiments at PSI

Experiment No. R-87-13, *Proposal to Study Multi-particle Final States in Pion-Nuclear Reactions with a Large Acceptance Detector (LADS),* Universität Basel, Carnegie-Mellon University, Universität Karlsruhe, LANL, University of Maryland, MIT, NAC–S. Africa, NIKHEF-K, PSI, University of Zagreb, and NMSU (Kyle, Klein, Mukhopadhyay, Wang); Q. Ingram, PSI, Spokesman.

The Large Acceptance Detector System (LADS) at the Paul Scherrer Insitute (PSI, near Zürich, Switzerland) was proposed in order to investigate multiparticle final states resulting from pion interactions in nuclei. The initial experiment, a survey of pion absorption reactions in ^{3,4}He and heavier nuclei, was approved with high priority in the summer of 1987. The primary interest was to investigate the long-outstanding question of the role of multinucleon pion absorption processes, and, should they be important, the possibility of exotic mechanisms.[52,53] However, the broader goal was to construct a general-purpose facility which would be suitable for investigations of a wide variety of quasifree reactions, in order to obtain more detailed information about the interactions of the pion, the nucleon, and the delta in nuclei. Such experiments require a detector having a solid-angle acceptance as close to 4π sr as possible and which can allow reconstruction of the full angle and energy information for all particles which participate in the reaction. The LADS construction was completed in two years at a cost of about one million Swiss francs, and the first data were obtained in the fall of 1989.

The design goals for LADS which we know or believe were achieved are summarized in Table 1. We note that a perfect general-purpose detector is impossible to realize; technical and cost considerations require some compromises. The design criteria for LADS were optimized toward the highest-priority physics (pion absorption reactions in light nuclei), while still allowing for future improvements, such as adding a good-resolution neutron detector or a magnetic field for better pion detection.

As shown in Fig. 14, LADS consists of a main cylindrical array of 28 telescopes of plastic scintillator having individual ΔE-E1-E2 counters read out at each end by photomultiplier tubes (PMT). The main cylinder is closed at each end by end-cap arrays consisting of 14 ΔE, 14 Inner-Veto, and 28 E counters. The light-guide geometry and PMT selection were optimized for good, uniform light collection. The PMT bases were designed to be linear to 400 MeV and gain-stable to about 1% at a rate of 10^5/sec of 100-MeV light pulses. The PMT gain variations are monitored by flashing a temperature-compensated light-emitting diode (LED) mounted on each counter. Prototype tests with a 100 MeV proton beam measured an energy resolution of 2.2 MeV and a timing resolution of 200 ps. Two cylindrical multiwire proportional counters (MWPC) of the SINDRUM type give information on the trajectories of the particles. The helium target is a pressurized gas cell in the shape of a cylinder 25 cm long and 4 cm in diameter, constructed of carbon fiber. At a pressure of 90 bar, the helium-to-window mass ratio is 2.2. Solid targets may

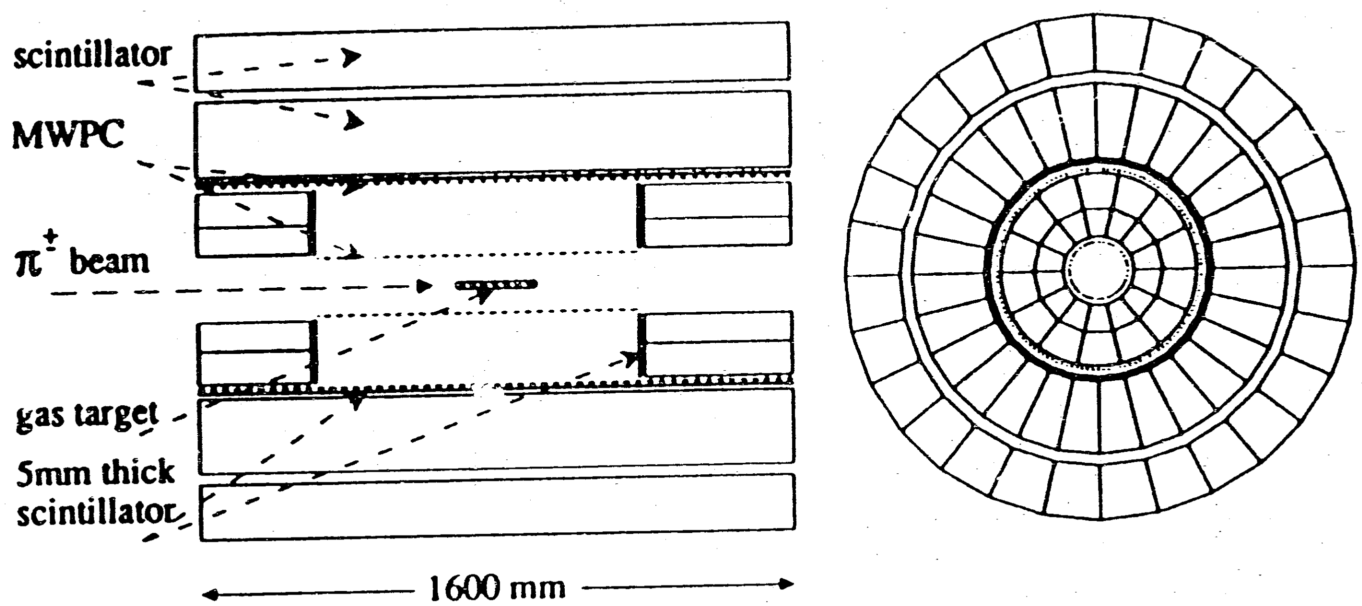

FIG. 14. Side and axial views of the detection components of LADS.

Table 1: LADS Parameters

Acceptance:	Ω	$\geq 98.8\% \times 4\pi$ sr.
	Threshold (p,n)	20 MeV
	Neutron efficiency	$\sim 40\%$
Kinematic Definition:	ΔT_p	$\leq 3\%$ at 100 MeV
	$\Delta\theta_p$	10–200 mr.
	ΔT_n	identify fast or slow
	$\Delta\theta_n$	$\sim 15^0$
Beam Rate:	up to 10^7/sec on target	
Particle Identification:	π,p,d at all energies	
	π^0/n, γ/n, π^+/π^- discrimination poor	

also be used. A pair of plastic scintillation counters selects beam bursts containing a single pion for triggering (using timing and energy loss information), define the beam spot size to avoid the target walls, and count the pion flux on target.

Most of the readout of the 280 PMT's is done with specially-constructed high-density electronics modules in FASTBUS. The raw PMT signals pass first into a Fast Discriminator/Mean Timer Module (FDMT) which outputs discriminated logic signals to FASTBUS latches and TDC's, analogue signals to the FERA ADC's, and mean-time signals for the trigger logic. The charged and neutral particle definition is done in a Programmable Logic Module (PLB), and their separate multiplicities are determined by a Multiplicity Logic Unit (MLU). NIM logic units are then used to produce several trigger types corresponding to combinations of charged and neutral particle multiplicities which may be separately prescaled. The MWPC anode wires, which give azimuthal position information, are read out by PCOS-III electronics, and the helical cathode strips, which give azimuithal and longitudinal position, are read out by CAMAC ADC's. An Aleph Event Builder (AEB) in FASTBUS reads the CAMAC and FASTBUS electronics, builds the event ($\sim$1Kb), and passes event buffers via Ethernet to a μVAX-III for taping and on-line analysis; event filtering may also be done in the AEB. The LADYBIRD acquisition software is built upon the standard PSI data acquisition system TANDEM. In 1989, the data acquisition rate was limited by the front-end system to about 50 events/sec. The planned upgrade of the front end with the addition of a CERN Host Interface (CHI) for the running in 1991 should increase the data rates by a factor of two or more.

NMSU was responsible for the design of the end-cap detectors and the construction of the 56 end-cap E counters. Much of the design and prototype testing was done during 1988 in our laboratory facilities on campus. In early 1989 our efforts moved to PSI, where we participated in the assembly of the detector components and the setup of the fast electronics. One of our group (Mukhopadhyay) also worked on the data acquisition and control software. We were also responsible for development of the Monte-Carlo code, which is based upon the CERN software package GEANT.

Running in the πM1 area began in July, 1989. Data taking began in late November and continued until the end of the year. Data were obtained for quasifree reactions in D and ^{4}He gas targets and in solid CD_2 for incident pion energies of 120 and in 165 MeV, and in ^{12}C, ^{58}Ni, and ^{181}Ta targets at 165 MeV. A portion of these data are under analysis at NMSU by M. Wang as part of his Ph.D. dissertation.

The analysis effort has been devoted to development of the off-line LADYBIRD software and the Monte Carlo program, careful checks of data consistency, calibration of the energy, timing, and position information, and development of the particle identification algorithm. Because of the large number of channels, the calibrations and cuts must be automated. The CPU and memory requirements are considerably greater than for most experiments we have done in the past, which makes low-cost dedicated workstations attractive. Therefore the analysis work at NMSU will be done on a VAXstation 3100/38 with a 1-Gigabyte external disk and an Exabyte 8-mm tape drive. This system provides over four times the processor speed and twice the available disk space of our VAX 11/750.

The data obtained in 1989 (which filled 250 9-track magnetic tapes) covers only about 10% of the proposed survey experiment. The PSI beams were shut down in January, 1990, for an upgrade to higher intensity operation. The shutdown is expected to extend until May, 1991, after which we plan to continue the survey measurements on the same targets with higher statistics and at additional energies. The expected data will fill about 2,500 9-track data tapes or about 200 8-mm video tapes. We anticipate further computing upgrades will be necessary for analysis of these large quantities of data.

Recent results indicate that multinucleon absorption processes with the emission of one or more energetic neutrons are important.[54,55] The LADS detector has good neutron detection efficiency, but poor neutron energy resolution, for reasons of cost. Instead, the LADS was designed to run at high beam intensities for efficient data taking with an external neutron time-of-flight wall in the trigger. We plan to include the neutron wall (at least parasitically) during the 1991 running.

The LADS detector has been the main focus of our program at PSI during the past three years. Much of of the impetus for its construction came from results of on-going programs of measurements of pion absorption at PSI, primarily those of the Basel-Karlsruhe-Zagreb groups, the Karlsruhe-Erlangen groups, and the Maryland-NMSU-PSI groups. Much of this work is still undergoing analysis, although preliminary results have been reported at several conferences. The experiments in which we have invested significant effort during the past three years are described below.

Experiment No. R-83-28, *A Measurement of the Reaction $^{16}O(\pi^+,pp)^{14}N$ over a Broad Kinematic Range for Pion Energies of 115 and 163 MeV*, University of Maryland, MIT, PSI, and NMSU (Kyle); G. Kyle, Spokesman.

This experiment studied the role of the simplest quasifree absorption process in which a pion is absorbed on a nucleon pair. The contribution of the two-nucleon process (often referred to as quasideuteron absorption) to the total absorption is a matter of controversy. The inclusive measurements of $^{12}C(\pi^+,pp)$ by Altmann suggested that the unperturbed two-nucleon process constituted only about 10% of the total absorption at $\Delta(1232)$ resonance energies.[56] Such a small contribution is difficult to reconcile with DWIA models, which successfully explain inclusive (π^+,p) data, and with more recent exclusive measurements of $^{58}Ni(\pi^+,pp)$.[57,58,59] In order to resolve these discrepancies, we undertook exclusive measurements which make possible a better separation of the two-nucleon absorption from the multinucleon "background" and also give information about the contributions from nucleons in different shells.

The experiment was performed at PSI using the SUSI spectrometer together with a large array of plastic scintillator telescopes. The energy resolution was sufficient to clearly identify the direct process, although individual states were not separated. Data were obtained for pion energies of 115 and 163 MeV for five spectrometer angles from 30^0 to 133^0. Data taking was completed in 1984. The data were analyzed by two Ph.D. students at Maryland.[60,61] The results, after correction for final state interactions, were that the two-nucleon process can explain about 75% of the total absorption cross section at 115 MeV. A substantial contribution from cross-shell absorption on s- and p-shell nucleon pairs was seen. At 165 MeV, the fraction dropped substantially to about 40%. The unperturbed two-nucleon cross section was about twice that reported by Altmann. A similar discrepancy was seen by Burger in the case of ^{58}Ni.[59] The source of disagreement apparently lies in the normalization of the data. Applying similar acceptance cuts to our data produced cross section angular correlations with similar shape but about twice the magnitude of those Altmann, as shown in Fig. 15. Therefore

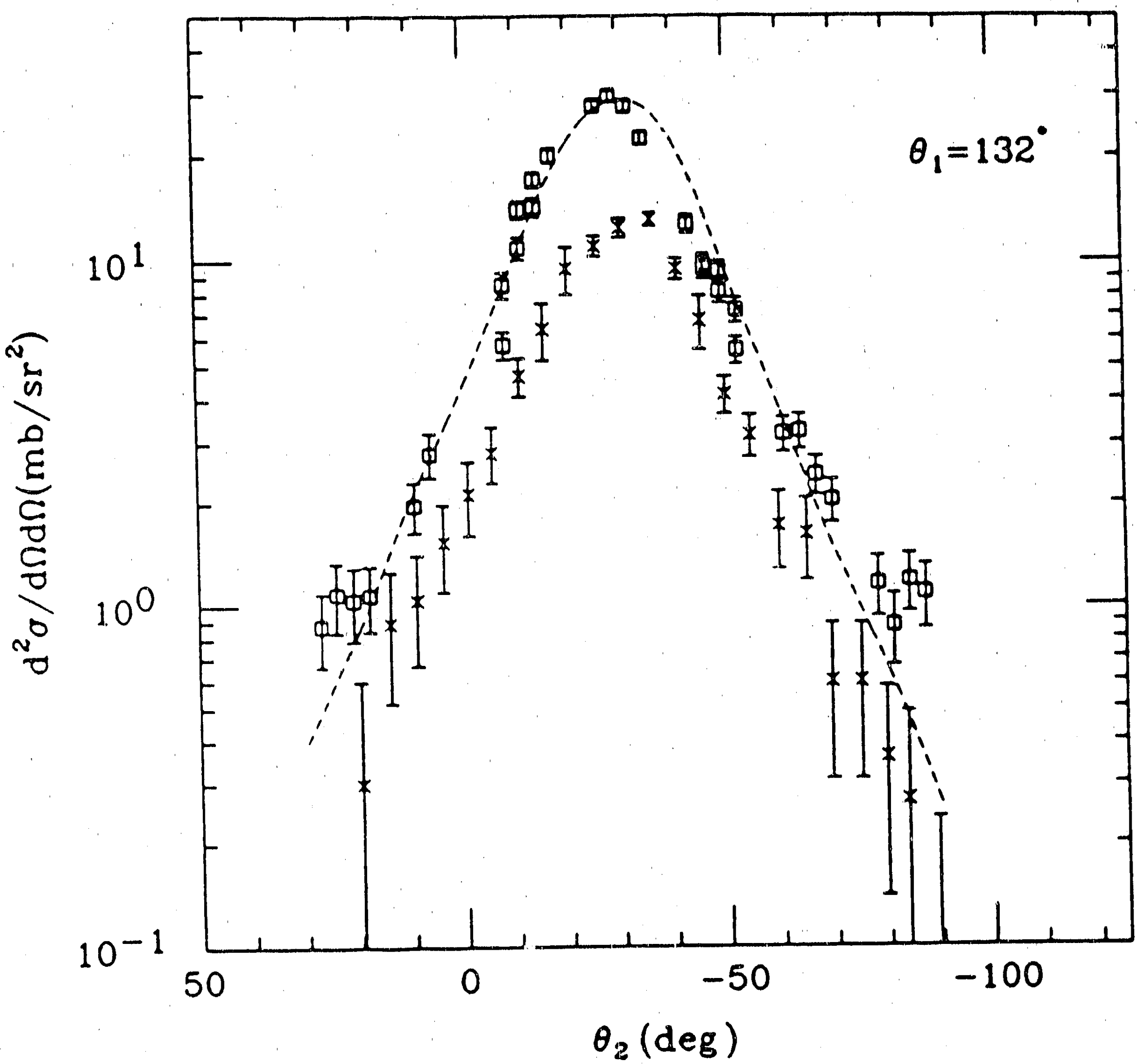

FIG. 15. Angular correlation data for $^{16}O(\pi^+,2p)^{14}N$ at 165 MeV, from Experiment No. R-83-28. These data are constrained to an out-of-plane angle of $\pm 6^0$. The squares are from Ref. [62] for $\theta_1 = 132^0$ and and the full excitation energy range of 0–140 MeV. The crosses are from Ref. [56] for $\theta_1 = 130^0$ shifted by 2^0. The dashed curve represents a smooth curve drawn through the data of Ref. [56] and renormalized by a factor of 2.3.

we believe that the Altmann experiment seriously under-reports the strength of two-nucleon absorption. However, our results also suggest that the two-nucleon process is dominant only at energies below the resonance. A brief report on the 165 MeV results has been published in the Physical Review, and the 115 MeV results have been submitted for publication.[62,63] A more complete paper is in preparation.

Experiment No. R-87-05.1, *A Study of the Reaction $^6Li(\pi^+,pp)$ over the Δ(1232) Resonance Region,* Arizona State University, University of Maryland, PSI, and NMSU (Kyle, Dhuga, Wang); P.G. Roos, Maryland, and G. Kyle, Spokesmen; and **LAMPF Experiment No. 948,** *Quasideuteron Absorption on ^6Li and ^{10}B,* Arizona State University, University of Maryland, University of South Carolina, and NMSU (Kyle, Rawool); B. G. Ritchie, ASU, Spokesman.

These complementary proposals studied the two-nucleon absorption process in ^{6}Li for eight energies between 30 and 220 MeV. The purposes were twofold: to measure the A-dependence of the two-nucleon process, and to compare the absorption on the loosely-bound valence nucleons with that on the tightly-bound core nucleons. The LAMPF experiment was run in December, 1986, and the PSI experiment followed in summer, 1987. The experimental details are described in our previous progress reports. The main difference between this PSI experiment and the one described above was replacement of the SUSI spectrometer by an array of NaI counters for increased acceptance. Students at Maryland (PSI) and Arizona State (LAMPF) have been analyzing these data as a part of their Ph.D. dissertations and have reported preliminary results.[64,65]

Experiment No. R-87-09, *Pion Absorption in Flight and Nucleon Multiplicities,* NIKHEF, University of Maryland, NIKHEF-K (Amsterdam), KFK Karlsruhe, PSI, and NMSU (Kyle, Mukhopadhyay, Wang); H. Breuer, Maryland, and Th.S. Bauer, NIKHEF, Spokesmen.

The primary goal of this experiment was a determination of the multiplicities of nucleons which participate in pion absorption near Δ(1232) resonance energies in ^{4}He and ^{16}O. It was motivated by the interesting behavior showed by the existing ^{3,4}He data. The total absorption cross section increased strongly from ^{3}He to ^{4}He, out of proportion to the increase in nucleon pairs, while the inelastic cross section showed a corresponding drop.[66,67] This suggested the possible onset of a strong four-nucleon absorption mode. The observation of a strong four-nucleon absorption channel would be very interesting, since it could arise from the $\Delta N \rightarrow \Delta\Delta$ process, which was predicted to be important in an SU(6) quark model.[52,53]

The experiment was based upon an earlier experiment at NIKHEF, which measured final-state nucleon multiplicities for the absorption of low-energy pions in ^{16}O using an array of plastic scintillator telescopes covering about half the full solid angle. The apparatus was moved to PSI for a few months in the summer of 1988. The reactions ^{4}He(π^+,2p)pn and ^{4}He(π^+,3p)n were measured at several energies from 65 to 330 MeV, and the NIKHEF measurements on ^{16}O were extended to 115 and 165 MeV. Although the solid-angle coverage for pppn final states where the energy is shared among the nucleons is poor (roughly 1 in 8 would be detected as ppp coincidences), the proton phase-space distributions when one or two nucleons are a spectator in the process tend toward coplanarity. Thus, with some model assumptions, a separation of the processes involving two, three, or four nucleons can be made. The data analysis is underway at the University of Maryland. Preliminary results have been reported.[68]

2.3 Other Projects

HERMES: *A Proposal to Measure the Deep Inelastic Spin-Dependent Structure Functions of the Nucleon at HERA,* Argonne National Laboratory, Caltech, MPI Heidelberg, University of Illinois–Urbana, LANL, University of Wisconsin, University of Marburg, MIT, University of München, Stanford University, Universita di Torino, TRIUMF/Alberta/Simon Fraser, College of William and Mary, and NMSU; R. Milner, MIT, and K. Rith, Heidelberg, Spokesmen.

Deep inelastic electron scattering has played a crucial role in the development of quantum chromodynaics (QCD). Within the parton picture, the deep inelastic structure functions provide information about the momentum distributions of quarks and gluons in the nucleons. The spin-dependent structure functions, measured using polarized beam and target, provide information on the spin distribution of partons in the nucleon.[69] Perturbative QCD makes definite predictions about the evolution of the structure functions with momentum transfer Q^2 and their shape at large x (the parton momentum fraction).[70,71,72] The dependence of the structure functions on x provides a constraint on hadron models, which contain ideas about the nonperturbative aspects of QCD and yield vastly different predictions for the spin-dependent structure functions of the nucleons. Of particular interest are the Bjorken[73] and Ellis-Jaffe[74] sum rules involving integrals of the spin structure functions. The Bjorken sum rule, which has not been experimentally tested, depends upon only very general properties such as current algebra. The Ellis-Jaffe sum rule, which seems to be violated by the experimental results on the proton, requires additional assumptions such as the absence of sea quark polarization.

Only two measurements, with rather large uncertainties, have been made of the spin-dependent structure function $g_1(x)$ for the proton,[75,76] and none have been made for the neutron. The results of these measurents have indicated the surprising result that the spin of the proton is not related very strongly to the spin of its quarks. This clearly should be investigated further.

The HERMES collaboration has proposed to measure the spin-dependent structure functions of the proton and neutron with a precision unmatched by other techniques, using the 30-GeV electron beam of the HERA accelerator at the DESY laboratory in Hamburg, Germany. The experiment involves scattering polarized electrons from polarized gas targets of hydrogen, deuterium and ^{3}He. The scattering asymmetries $A_1(x)$ and $A_2(x)$ can be measured with much higher precision than previously because of the high current (60 mA) and polarization (60%) expected for the beam and the low dilution of polarized nucleons in the gas targets. The experiment will also set upper limits for two deuteron structure functions, $b_1(x)$ and $\Delta(x)$, which are expected to be small but which in principal can contribute to the de... inelastic cross section for a polarized deuteron target.

The proposal for this experiment was presented to the Physics Research Committee (PRC) at DESY in March and September, 1990. We understand that approval was recommended, under two conditions: demonstration of target density and polarization, and demonstration of 60% transverse electron beam polarization. Work on these two items is planned to take place during the coming year, by the collaboration (target) and by the laboratory (beam).

The detector system would consist of a magnetic volume with tracking multiwire proportional chambers for primary energy measurement, a transition radiation detector for hadron rejection, a trigger hodoscope, and a calorimeter for background rejection which serves as a second-level trigger. We have proposed to work together with Caltech, Illinois, and Los Alamos on the calorimeter, and one of our students would also analyze a portion of the data. In particular, we expect to work closely with the Los Alamos group on those aspects of the calorimeter project which overlap with the new Neutral Meson Spectrometer (NMS) under development at LAMPF, which we plan to use for future experiments. Two of our students, Kevin Cranston and Maher El-Ghossain, have been involved in testing photomultiplier tubes for these projects. This work has involved constructing a large black box and a remotely-controlled holder of neutral density filters which are used with a light pulser and a PC-based pulse-height analyzer. Work with this system has been carried out both at NMSU and at Los Alamos.

Instrumentation: For LAMPF Exp. 1023/1025 one of us (Klein) developed a device to monitor the profile and position of the pion beam in the Low Energy Pion Channel. In an experiment to measure asymmetries, it is important to monitor the position of the beam in order to prevent introducing false asymmetries into the data. For these experiments a monitor had to be designed to operate in the 2.5-T magnetic field of the polarizing magnet and to give a resolution of about 3 mm FWHM. Our device consisted of a scintillating fiber matrix of 30 × 30 × 20 mm made of 1-mm-square fibers supplied by the BICRON Corporation. The matrix was optically coupled to a 1-m-long plastic fiber bundle made of 1-mm-round fibers. This light transport mechanism was necessary to allow the photomultiplier to be positioned out of the region of high field. The fiber bundle was coupled to a position-sensitive photomultiplier tube obtained from Hamamatsu. This device has a grid of 16 × 16 anode wires and an active area of 58 × 58 mm. In the electronics, the amplified and discriminated signals were sent to ADC's, TDC's, and logic units. A beam particle event was taken to be a coincidence between one x and one y signal. The position of the particle was calculated from the charge on the dynodes. The TDC information was used to separate events in different beam spills in order to eliminate ambiguities. The resolution was about 5 mm.

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3 Publications

The following is a list of publications of the NMSU group between July 1, 1987, and October 1, 1990. Some of these report work that was supported under DOE Contract No. DE-AS04-76ER03591, the predecessor of the current grant, which had not been listed in the progress reports of that contract. The names of the authors supported by DOE under that contract or this grant are in bold type.

3.1 Published Papers

1. *Measurements of C_{LL} and C_{SL} for Elastic np Scattering at 484 and 634 MeV*, **G. R. Burleson, J. A. Faucett, C. A. Fontenla, R. W. Garnett, M. W. Rawool**, W. R. Ditzler, D. Hill, J. Hoftiezer, K. F. Johnson, D. Lopiano, T. Shima, H. Shimizu, H. Spinka, R. Stanek, D. Underwood, R. Wagner, A. Yokosawa, T. S. Bhatia, G. Glass, J. C. Hiebert, R. A. Kenefick, S. Nath, L. C. Northcliffe, R. Damjanovich, J. J. Jarmer, R. H. Jeppesen, and G. E. Trippard; Phys. Rev. Lett. **59**, 1645 (1987).
2. *Double Charge Exchange to the Double Isobaric Analog State at T_p=292 MeV*, J. D. Zumbro, H. T. Fortune, M. Burlein, C. L. Morris, Z.-F. Wang, R. Gilman, **K. S. Dhuga, G. R. Burleson, M. W. Rawool, R. W. Garnett**, M. J. Smithson, D. S. Oakley, S. Mordechai, C. F. Moore, M. A. Machuca, D. L. Watson, and N. Auerbach; Phys. Rev. C **36**, 1479 (1987).
3. *Pi^+ Absorption on ^{12}C in the Delta(1232) Region*, W. Brueckner, H. Doebbeling, P. C. Gugelot, F. Guettner, H. Kneis, S. Majewski, M. Nomachi, S. Paul, B. Povh, R. D. Ransome, T.-A. Shibata, M. Treichel, Th. Walcher, P. Amaudruz, Th. Bauer, J. Domingo, R. Frey, Q. Ingram, H. Jantzen, **G. Kyle**, D. Renker, R. Schumacher; Nucl. Phys. **A469**, 617 (1987).
4. *First Measurement of the Tensor Analyzing Power T_{21} in πd Elastic Scattering*, G. R. Smith, D. R. Gill, D. Healey, D. Otwell, G. D. Wait, P. Walden, R. R. Johnson, G. Jones, R. Olszewski, F. M. Rozon, R. Rui, M. E. Sevior, R. P. Trelle, E. L. Mathie, G. L. Lolos, C. R. Otterman, W. Gyles, and **G. S. Kyle**; Phys. Rev. C **35**, 2343 (1987).
5. *Inelastic Scattering from ^{12}C*, **W. B. Cottingame**, K. G. Boyer, W. J. Braithwaite, S. J. Greene, C. J. Harvey, R. J. Joseph, D. B. Holtkamp, C. F. Moore, J. J. Kraushaar, R. J. Peterson, R. A. Ristinen, J. R. Shepard, G. R. Smith, R. L. Boudrie, N. S. P. King, C. L. Morris, J. Piffaretti, and H. A. Thiessen; Phys. Rev. C **36**, 230 (1987).

6. *Giant Double Resonances Built on Isobaric Analog States in Pion Double Charge Exchange*, S. Mordechai, N. Auerbach, **G. R. Burleson, K. S. Dhuga**, M. Dwyer, **J. A. Faucett**, H. T. Fortune, R. Gilman, S. J. Greene, C. Layman, C. F. Moore, C. L. Morris, D. S. Oakley, M. A. Plum, S. J. Seestrom-Morris, P. A. Seidl, M. J. Smithson, Z. F. Wang, and J. D. Zumbro; Phys. Rev. Lett. **60**, 408 (1988).

7. *Construction and Operation of a $3m \times 1m$ Drift Chamber*, W. Haberichter, T. Kasprzyk, H. Shimizu, R. Stanek, **G. Burleson, R. Garnett**, and J. Tobin; Nucl. Instr. and Methods **A270**, 361 (1988).

8. *Pion Double Charge Exchange to the Double Dipole Resonance*, S. Mordechai, N. Auerbach, M. Burlein, H. T. Fortune, S. J. Greene, C. F. Moore, C. L. Morris, J. M. O'Donnell, **M. W. Rawool**, J. D. Silk, D. L. Watson, S. H. Yoo, and J. D. Zumbro; Phys. Rev. Lett. **61**, 531 (1988).

9. *Exclusive Quasi-deuteron Absorption of Pions in ^{16}O and ^{18}O at 116 MeV*, R.A. Schumacher, P.-A. Amaudruz, Q. Ingram, U. Sennhauser, H. Breuer, N. Chant, A. Feldman, B. Flanders, F. Khazaie, D. Mack, P. Roos, J. Silk, and **G. S. Kyle**, Phys. Rev. C **38**, 2205–2220 (1988).

10. *Energy Dependence of T_{20} and τ_{21} in πd Elastic Scattering*, G. R. Smith, D. R. Gill, D. Healey, D. Ottwell, G. D. Wait, P. Walden R. R. Johnson, G. Jones, R. Olszewski, F. M. Rozon, R. Rui, M. E. Sevior, R. P. Trelle, E. L. Mathie, G. Lolos, S. I. H. Naqvi, V. Pafilis, N. R. Stevenson, R. B. Schubank, W. Gyles, C. R. Ottermann, and **G. Kyle**, Phys. Rev. C **38**, 251 (1988).

11. *Measurement of a Mixed Spin-Spin Correlation Parameter for np Elastic Scattering,* **R. Garnett, M. Rawool**, V. Carlson, D. Hill, K. F. Johnson, D. Lopiano, Y. Ohashi, T. Shima, H. Spinka, R. Stanek, D. Underwood, A. Yokosawa, **M. Beddo, G. Burleson, J. A. Faucett, G. Kyle**, H. Shimizu, G. Glass, S. Nath, L. C. Northcliffe, J. J. Jarmer, R. H. Jeppesen, and G. E. Trippard; Phys. Rev. C **40**, 1708 (1989).

12. *Spin-Correlation Parameter $A_{nn}(\Theta^*)$ for n-p Elastic Scattering at 790 MeV*, S. Nath, G. Glass, J. C. Hiebert, J. A. Holt, R. A. Kenefick, L. C. Northcliffe, D. P. Grosnick, D. Lopiano, Y. Ohashi, T. Shima, H. M. Spinka, R. Stanek, T. S. Bhatia, J. J. Jarmer, P. J. Riley, S. Sen, **J. A. Faucett, G. Kyle**, R. H. Jeppesen, and G. Trippard; Phys. Rev. D **39**, 3520 (1989).

13. *Pion Double Charge Exchange above the $\Delta(1232)$ Resonance,* A. L. Williams, L. Agnew, L. G. Atencio, H. W. Baer, M. Burlein, **G. R Burleson, K. S. Dhuga**, H. T. Fortune, **G. S. Kyle**, J. A. McGill, C. Fred Moore, C. L. Morris, S. Mordechai,

J. M. O'Donnell, **M. W. Rawool**, S. Schilling, J. D. Silk, and J. D. Zumbro; Phys. Lett. **B216**, 11 (1989).

14. *Inelastic Scattering of Pions by* ^{10}B, B. Zeidman, D. F. Geesaman, P. Zupranski, R. E. Siegel, G. C. Morrison, C. Olmer, **G. R. Burleson, S. J. Greene**, R. L. Boudrie, C. L. Morris, L. W. Swenson, G. S. Blanpied, and C. L. Harvey Johnstone; Phys. Rev. C **38**, 2251 (1989).
15. *Pion Inelastic Scattering to the Low-Lying Broad* 2^+ *in* ^{20}Ne, M. Burlein, H. T. Fortune, W. M. Amos, T. Ekenberg, A. Kotwai, P. H. Kutt, R. Boyer, A. Fuentes, K. Johnson, C. F. Moore, S. H. Yoo, S. Mordechai, C. L. Morris, J. D. Zumbro, D. L. Watson, and **K. S. Dhuga**; Phys. Rev. C **40**, 785 (1989).
16. $^{16}O(\pi^+,2p)$ *Reaction at 165 MeV*, S. D. Hyman, D. J. Mack, H. Breuer, N. S. Chant, F. Khazaie, B. G. Ritchie, P. G. Roos, J. D. Silk, P.-A. Amadrus, Th. S. Bauer, C. H. Q. Ingram, **G. S. Kyle**, D. Renker, R. A. Schumacher, U. Sennhauser, and W. J. Burger; Phys. Rev. C **41**, 409 (1990).
17. *Analyzing Power Measurements for Forward Angle n-p Scattering at 790 MeV*, G. Glass, T. S. Bhatia, J. C. Hiebert, R. A. Kenefick, S. Nath, L. C. Northcliffe, K. F. Johnson, H. Spinka, R. Stanek, **M. W. Rawool, J. A. Faucett**, R. H. Jeppesen, G. E. Trippard, and C. R. Newsom; Phys. Rev. C **41**, 2732 (1990).
18. *Negative Pion-Nucleus Elastic Scattering at 30 and 50 MeV*, K. K. Seth, D. Barlow, S. Iversen, M. Kaletka, H. Nann, D. Smith, **G. Burleson, G. Blanpied, G. Daw**, W. J. Burger, R. P. Redwine, B. Saghai, and R. Anderson; Phys. Rev. C **41**, 2800 (1990).

3.2 Papers Submitted for Publication

1. *Dominance of the Two-Nucleon Mechanism in* $^{16}O(\pi^+,pp)$ *at 115 MeV*, D. J. Mack, H. Breuer, N. S. Chant, S. D. Hyman, F. Khazaie, B. G. Ritchie, P. G. Roos, J. D. Silk, **G. Kyle**, P.-A. Amaudruz, Th. S. Bauer, C. H. Q. Ingram, D. Renker, R. A. Schumacher, U. Sennhauser, and W. J. Burger; submitted to Phys. Rev. C.
2. *Pion Double Charge Exchange on* $^{42,44,48}Ca$ *for* $300 \leq T_\pi \leq 550$ *MeV*, A. L. Williams, J. A. McGill, C. L. Morris, **G. R. Burleson, J. A. Faucett**, D. S. Oakley, M. Burlein, H. T. Fortune, J. M. O'Donnell, G. P. Kahrimanis, and C. F. Moore; submitted to Phys. Rev. C.
3. *Polarized Proton Elastic Scattering from Polarized* ^{13}C, G. W. Hoffmann, M. L. Barlett, W. Kielhorn, G. Pauletta, M. Purcell, L. Ray, J. F. Amann, J. J. Jarmer,

K. W. Jones, S. Penttilä, N. Tanaka, **G. Burleson, J. Faucett**, M. Gilani, **G. Kyle, L. Stevens**, T. Mack, D. Mihailidis, D. Dehnhard, T. Averett, J. Comfort. J. Görgen. J. Tinsley. B. C. Clark. S. Hama and R. L. Mercer; submitted to Phys. Rev. Lett.

4. *Analyzing Powers for the Reaction $\pi^- \vec{p} \rightarrow \pi^0 n$ at $T_{\pi^-} = 161$ MeV*, J. J. Görgen, J. R. Comfort, T. Averett, J. DeKorse, B. Franklin, B. G. Ritchie, J. Tinsley, **G. Kyle, B. Berman, G. Burleson, K. Cranston, A. Klein**, J. A. Faucett, J. J. Jarmer, J. N. Knudson, S. Penttilä, N. Tanaka, B. Brinkmöller, D. Dehnhard, Y. F. Yen, S. Høibråten, H. Breuer, B. S. Flanders, M. A. Khandaker, D. L. Naples, D. Zhang, M. L. Barlett, G. W. Hoffmann, and M. Purcell; submitted to Phys. Rev. D.

5. *Pion Double Charge Exchange on $T = 2$ Nuclei*, P. A. Seidl, M. A. Bryan, M. Burlein, **G. R. Burleson, K. S. Dhuga**, H. T. Fortune, R. Gilman, S. J. Greene, M. A. Machuca, C. F. Moore, S. Mordechai, C. L. Morris, D. S. Oakley, M. A. Plum, G. Rai, M. J. Smithson, Z. F. Wang, D. L. Watson, and J. D. Zumbro; submitted to Phys. Rev. C.

6. *Analyzing Powers for Pion Charge Exchange on a Polarized ^{13}C Target*, J. J. Görgen, J. R. Comfort, T. Averett, J. DeKorse, B. Franklin, B. G. Ritchie, J. Tinsley, **G. Kyle, B. Berman, G. Burleson, K. Cranston, A. Klein**, J. A. Faucett, J. J. Jarmer, J. N. Knudson, S. Penttilä, N. Tanaka, B. Brinkmöller. D. Dehnhard, Y. F. Yen, S. Høibråten, H. Breuer, B. S. Flanders, M. A. Khandaker, D. L. Naples, D. Zhang, M. L. Barlett, G. W. Hoffmann, and M. Purcell; submitted to Phys. Rev. C.

7. *Pion Elastic Scattering from Polarized ^{13}C in the Energy Region of the (3,3) Resonance*, Y.-F. Yen, B. Brinkmöller, D. Dehnhard, Y.-J. Yu, **B. Berman, G. R. Burleson, K. Cranston, A. Klein, G. S. Kyle**, R. Alarcon, T. Averett, J. R. Comfort, J. Görgen, R. Ritchie, A. Williams, J. A. Faucett, S. J. Greene, J. Jarmer, J. A. McGill, C. L. Morris, S. Penttilä, N. Tanaka, H. T. Fortune, E. Insko, R. Ivie, J. M. O'Donnell, D. Smith, S. Høibråten, M. A. Khandaker, and S. Chakravarti; submitted to Phys. Rev. Lett.

3.3 Papers Presented at Meetings and Conferences

At the Spring Meeting of the American Physical Society, Baltimore, Maryland, April 18–21, 1988:

1. *Measurement of the Reaction $^{16}O(\pi^+,2p)^{14}N$ at 165 MeV*, S. D. Hyman, H. Breuer, N. S. Chant, F. Khazaie, D. Mack, B. G. Ritchie, P. G. Roos, J. D. Silk, P. A. Amadruz, Th. S. Bauer, **G. Kyle**, C. Q. Ingram, D. Renker, R. A. Schumacher, U. Sennhauser, and W. J. Burger; Bull. Am. Phys. Soc. **33**, 902 (1988).
2. *$^{10}B(\pi^+,2p)$ at 115 MeV*, B. G. Ritchie, D. Rothenberger, J. R. Comfort, R. A. Giannelli, J. Tinsley, N. S. Chant, D. Mack, P. G. Roos, J. D. Silk, **G. S. Kyle, M. Rawool**, J. A. Escalante, and B. M. Preedom; Bull. Am. Phys. Soc. **33**, 903 (1988).
3. *Low Energy Positive Pion Absorption on ^6Li*, D. Rothenberger, B. G. Ritchie, J. R. Comfort, R. A. Giannelli, J. Tinsley, N. S. Chant, D. Mack, P. G. Roos, J. D. Silk, **G. S. Kyle, M. Rawool**, J. A. Escalante, and B. M. Preedom; Bull. Am. Phys. Soc. **33**, 903 (1988).
4. *Measurement of the Spin Correlation Parameter A_{NN} for n-p Elastic Scattering at 800 MeV*, S. Nath, G. Glass, J. Hiebert, J. Holt, R. Kenefick, L. Northcliffe, D. Lopiano, Y. Ohashi, T. Shima, H. Spinka, R. Stanek, T. Bhatia, J. Jarmer, P. Riley, S. Sen, R. Jeppesen, G. Trippard, **J. Faucett**, and **G. Kyle**; Bull. Am. Phys. Soc. **33**, 962 (1988).
5. *Measurement of C_{LL}, C_{SL}, and C_{SS} in np Elastic Scattering at 484 and 634 MeV*, **R. Garnett, M. Beddo, G. Burleson, J. Faucett, G. Kyle**, C. Luchini, **M. Rawool**, V. Carlson, D. Hill, K. Johnson, D. Lopiano, Y. Ohashi, T. Shima, H. Spinka, R. Stanek, D. Underwood, A. Yokosawa, H. Shimizu, G. Glass, S. Nath, L. Northcliffe, R. Damjanovich, J. Jarmer, R. Jeppesen, and G. Trippard; Bull. Am. Phys. Soc. **33**, 1100 (1988).
6. *Kinematic Signature of Two Step Pion Scattering to the Continuum*, J. D. Silk, M. Burlein, H. T. Fortune, J. M. O'Donnell, C. L. Morris, J. A. McGill, **G. S. Kyle**, and D. L. Watson; Bull. Am. Phys. Soc. **33**, 1487 (1988).

At the Third Conference on the Intersections Between Particle and Nuclear Physics, Rockport, Maine, May 14–19, 1988:

1. *Measurements of C_{LL}, C_{SL}, and C_{SS} in np Elastic Scattering at 484, 634, and 784 MeV*, **G. Burleson, M. Beddo, J. Faucett, C. Fontenla, R. Garnett,**

G. Kyle, C. Luchini, **M. Rawool**, V. Carlson, R. Ditzler, D. Hill, J. Hoftiezer, K. Johnson, D. Lopiano, Y. Ohashi, T. Shima, H. Shimizu, H. Spinka, R. Stanek, D. Underwood, R. Wagner, A. Yokosawa, T. Bhatia, G. Glass, J. Hiebert, R. Kenefick, S. Nath, L. Northcliffe, R. Damjanovich, J. Jarmer, R. Jeppesen, and G. Trippard.

2. *Coincidence Measurements of Pion Single Charge Exchange in the Δ-resonance Region*, S. Höibraten, S. Gilad, W. J. Burger, G. W. Dodson, G. Gatoff, L. D. Pham, R. P. Redwine, E. [illegible]setzky, H. W. Baer, J. D. Bowman, F. H. Cverna, F. Irom, M. J. Leitch, U. Sennhauser, J. N. Knudson, Th. S. Bauer, C. H. Q. Ingram, **G. S. Kyle**, D. Ashery, S. A. Wood, S. H. Rokni, and Z. Fraenkel.

At the Annual Meeting of the Division of Nuclear Physics of the American Physical Society, Santa Fe, New Mexico, October 13–15, 1988:

1. *Measurement of the Reaction $^{6}Li(\pi^{+},2p)^{4}He$ over the Δ(1232) Resonance Region*, D. Zhang, H. Breuer, N. S. Chant, B. S. Flanders, S. D. Hyman, D. J. Mack, P. G. Roos, J. D. Silk, **K. Dhuga, G. S. Kyle, M. Wang**, P.-A. Amadruz, W. J. Burger, C. H. Q. Ingram, R. A. Schumacher, U. Sennhauser, B. G. Ritchie, and D. Rothenberger; Bull. Am. Phys. Soc. **33**, 1586 (1988).
2. *Coincidence Measurements of the Reaction $^{16}O(\pi^{+},2p)^{14}N$ at 165 MeV.* S. D. Hyman, H. Breuer, N. S. Chant, F. Khazaie, D. Mack, B. G. Ritchie, P. G. Roos, J. D. Silk, P. A. Amadruz, Th. S. Bauer, **G. Kyle**, C. H. Q. Ingram, D. Renker, R. A. Schumacher, U. Sennhauser, and W. J. Burger; Bull. Am. Phys. Soc. **33**, 1607 (1988).
3. *Dominance of the Two-Nucleon Mechanism in $^{16}O(\pi^{+},2p)$ at 115 MeV*, D. Mack, H. Breuer, N. S. Chant, F. Khazaie, B. G. Ritchie, P. G. Roos, J. D. Silk, P. A. Amaudruz, Th. S. Bauer, C. H. Q. Ingram, **G. Kyle**, D. Renker, R. A. Schumacher, U. Sennhauser, and W. Burger; Bull. A. Phys. Soc. **33**, 1587 (1988).
4. *Measurement of C_{SS} in np Elastic Scattering at 484, 634, and 788 MeV*, **R. Garnett, M. Beddo, G. Burleson, J. Faucett, G. Kyle**, C. Luchini, **M. Rawool**, V. Carlson, D. Hill, K. Johnson, D. Lopiano, Y. Ohashi, T. Shima, H. Spinka, R. Stanek, D. Underwood, A. Yokosawa, H. Shimizu, G. Glass, S. Nath, L. Northcliffe, R. Damjanovich, J. Jarmer, R. Jeppesen, and G. Trippard; Bull. Am. Phys. Soc. **33**, 1597 (1988).
5. *Neutron Detector Efficiency for a Large Scintillator Hodoscope*, M. Devereux, **M. Beddo, G. Burleson, J. Faucett, R. Garnett, G. Kyle, M. Rawool**, D. Grosnick, D. Lopiano, Y. Ohashi, T. Shima, H. Spinka, D. Underwood, G.

Glass, L. Northcliffe, R. Jeppesen, and G. Trippard; Bull. Am. Phys. Soc. **33**, 1577 (1988).

At the LAMPF Users Group Meeting, Los Alamos, New Mexico, October 17–18, 1988:

1. *Quasi-free Pion-Nucleus Reactions*, **G. Kyle**; invited paper.

At the Annual Meeting of the Texas Section of the American Physical Society and the American Association of Physics Teachers, Lubbock, Texas, November 4–5, 1988:

1. *Experimental Features of Pion Absorption at $\Delta(1232)$ Resonance Energies*, **G. Kyle**, H. Breuer, N. Chant, F. Khazaie, D. Mack, B. Ritchie, P. Roos, J. Silk, P. A. Amaudruz, Th. S. Bauer, C. H. Q. Ingram, D. Renker, U. Sennhauser, R. Schumacher, and W. Burger.

At the Spring Meeting of the American Physical Society, Baltimore, Maryland, May 1–4, 1989:

1. *$\pi^{\pm}$ - ^{4}He Elastic Scattering at Far Forward and Far Backward Angles*, B. Brinkmöller, D. Dehnhard, M. K. Jones, S. M. Sterbenz, Yi-Fen Yen, C. L. Morris, S. J. Seestrom-Morris, S. J. Greene, **G. R. Burleson**, **K. S. Dhuga**, **J. A. Faucett**, **R. Garnett**, C. F. Moore, S. Mordechai, D. Oakley, M. Smithson, A. Williams, and S. Yoo; Bull. Am. Phys. Soc. **34**, 1203 (1989).
2. *Pion Inelastic Scattering to the Low-Lying Broad 2^{+} in ^{20}Ne*, M. Burlein, W. M. Amos, T. L. Ekenberg, H. T. Fortune, A. V. Kotwal, P. H. Kutt, J. M. O'Donnell, J. D. Silk, C. L. Morris, J. D. Zumbro, D. L. Watson, C. F. Moore, B. Boyer, A. Fuentes, K. Johnson, S. H. Yoo, and **K. S. Dhuga**; Bull. Am. Phys. Soc. **34**, 1204 (1989).
3. *$^{6}Li(\pi^{+},2p)^{4}He$ at Low Energies*, D. Rothenberger, B. G. Ritchie, J. R. Comfort, R. A. Giannelli, J. R. Tinsley, N. S. Chant, D. J. Mack, R. G. Roos, J. D. Silk, **G. S. Kyle**, **M. Rawool**, J. A. Escalante, and B. M. Preedom; Bull. Am. Phys. Soc. **34**, 1204 (1989).
4. *Energy Dependence of the $^{6}Li(\pi^{+},2p)$ Reaction*, D. Zhang, H. Breuer, N. S. Chant, B. S. Flanders, S. D. Hyman, D. J. Mack, P. G. Roos, J. D. Silk, **K. Dhuga**, **G. S. Kyle**, **M. Wang**, P.-A. Amadruz, C. H. Q. Ingram, R. A. Schumacher,

U. Sennhauser, J. Jacob, B. G. Ritchie, D. Rothenberger, J. McDonald, and A. Williams; Bull. Am. Phys. Soc. **34**, 1205 (1989).

5. *Inclusive and Exclusive Measurements of the Reaction* $^{16}O(\pi^+,p)$ *and* $^{16}O(\pi^+,2p)$ *at 165 MeV,* S. D. Hyman, H. Breuer, N. S. Chant, F. Khazaie, D. Mack, B. G. Ritchie, P. G. Roos, J. D. Silk, P. A. Amadruz, Th. S. Bauer, **G. Kyle**, C. H. Q. Ingram, D. Renker, R. A. Schumacher, U. Sennhauser, and W. J. Burger; Bull. Am. Phys. Soc. **34**, 1205 (1989).

At the Annual Meeting of the Division of Nuclear Physics of the American Physical Society, Asilomar, California, Oct 12–14, 1989:

1. *500 MeV Elastic* $\vec{p}$ + $^{13}\vec{C}$ *Analyzing Power Measurements,* G. Hoffmann, M. Barlett, W. Kielhorn, G. Pauletta, M. Purcell, L. Ray, J. Amann, J. Jarmer, K. Jones, S. Penttilä, N. Tanaka, **G. Burleson, J. Faucett**, M. Gilani, **G. Kyle, L. Stevens**, T. Mack, D. Mihailidis, T. Averett, J. Comfort, J. Görgen, J. Tinsley, B. Clark, S. Hama, and R. Mercer; Bull. Am. Phys. Soc. **34**, 1829 (1989).

At the Second LAMPF Workshop on Pion Double Charge Exchange, Los Alamos, New Mexico, August 9–11, 1989:

1. *The High-Energy Experimental Program,* **G. R. Burleson**; invited paper, to be published in the Proceedings by World Scientific Publishing Co.

At the LAMPF Users Group Meeting, Los Alamos, New Mexico, August 14–15, 1989:

1. *Report from the Pion Physics Working Group,* **G. R. Burleson**; invited paper.

At the Workshop on Large Acceptance Detectors for IUCF, Indiana University, Bloomington, Indiana, December 1–2, 1989:

1. *The Large Acceptance Detector System at PSI,* **G. S. Kyle**; invited paper.

At the Spring Meeting of the American Physical Society, Washington, D. C. April 16–19, 1990:

1. *Study of Energy Dependence of the* $^6Li(\pi^+,2p)$ *Reaction around the* $\Delta(1232)$ *Resonance Region,* D. Zhang, H. Breuer, N. S. Chant, B. S. Flanders, S. D. Hyman, M. A. Khandakar, D. J. Mack, P. G. Roos, J. D. Silk, **K. Dhuga, G. S. Kyle,**

M. Wang, P.-A. Amadruz, C. H. Q. Ingram, R. A. Schumacher, U. Sennhauser, J. Jacob, B. G. Ritchie, D. Rothenberger, J. McDonald, and A. Williams; Bull. Am. Phys. Soc. **35**, 946 (1990).

2. *Multi-Nucleon Pion Absorption in $^4He(\pi^+, x, ...)$ Reaction*, F. Adimi, M. Khayat, H. Breuer, B. Flanders, M. Khandakar, P. G. Roos, D. Zhang, Th. S. Bauer, J. Konijn, C. T. A. M. DeLaat, **G. Kyle, S. Mukhopadhyay, M. Wang**, and R. Tacik; Bull. Am. Phys. Soc. **35**, 945.

3. *500 MeV Elastic $\vec{p}$ + $^{13}\vec{C}$ Analyzing Power Measurements*, G. W. Hoffmann, M. L. Barlett, W. Kielhorn, G. Pauletta, M. Purcell, L. Ray, J. F. Amann, J. J. Jarmer, K. W. Jones, S. Penttilä, N. Tanaka, **G. Burleson, J. Faucett**, M. Gilani, **G. Kyle, L. Stevens**, T. Mack, D. Mihailidis, D. Dehnhard, T. Averett, J. Comfort. J. Görgen. J. Tinsley. B. C. Clark. S. Hama and R. L. Mercer; Bull. Am. Phys. Soc. **35**, 1038 (1990).

At the Second International Conference on Medium- and High-Energy Nuclear Physics, Taipei, Taiwan, May 14–18, 1990:

1. *Pion Double Charge Exchange above the Delta Resonance*, **G. R. Burleson**; invited paper, to be published in the Proceedings by Elsevier Science Publishing Company.

At the US-Japan Seminar on Pion-Nucleus Interactions above the Delta Resonance, Tsuchiura, Japan, May 21–24, 1990:

1. *Pion Double Charge Exchange above the Delta Resonance*, **G. R. Burleson**; invited paper.

At the Twelfth International Conference on Particles and Nuclei, Massachusetts Institute of Technology, Cambridge, Massachusetts, June 25–29, 1990:

1. *Proton Elastic Scattering from Polarized ^{13}C at 500 MeV*, G. Hoffman, M. Barlett, W. Kielhorn, G. Pauletta, L. Ray, J. Amann, J. Jarmer, K. Jones, S. Penttilä, N. Tanaka, **G. Burleson, J. Faucett**, M. Gilani, **G. Kyle, L. Stevens**, T. Mack, K. Mihailidis, D. Dehnhard, T. Averett, J. Comfort, J. Görgen, J. Tinsley, B. Clark, and S. Hama. (Paper selected for oral presentation.)

2. *A Large Acceptance Detector System for Pion Reaction Studies*, G. Backenstoss, H. Breuer, E. Daum, H. Döbbeling, M. Furic, P. A. M. Gram, A. Hoffart, C. H. Q.

Ingram, **A. Klein**, B. Kotlinski, **G. S. Kyle**, K. Michaelian, **S. Mukhopadhyay**, T. Petrovic, R. P. Redwine, D. Rowntree, R. A. Schumacher, U. Sennhauser, N. Simicevic, F. D. Smit, G. van der Steenhoven, D. R. Tieger, H. Ullrich, S. Vinzelberg, **M. H. Wang**, D. Weiser, H. J. Weyer, M. Wildi, and K. E. Wilson. (Paper selected for oral presentation.)

3. *Asymmetry Measurements of Pion Elastic Scattering from Polarized* ^{13}C, Y. F. Yen, B. Brinkmöller, S. Chakravarti, D. Dehnhard, S. M. Sterbenz, Y. J. Yu, **B. Berman, G. R. Burleson, K. Cranston, A. Klein, G. S. Kyle**, R. Alarcon, T. Averett, J. R. Comfort, J. Görgen, B. Ritchie, J. M. Tinsley, G. W. Hoffmann, K. Johnson, M. Purcell, H. Ward, A. Williams, J. A. Faucett, S. J. Greene, J. J. Jarmer, J. A. McGill, C. L. Morris, S. Penttilä, N. Tanaka, E. Insko, R. Ivie, J. M. O'Donnell, D. Smith, S. Høibråten, and M. Khandaker.

4. *High energy Pion Double Charge Exchange on* $(f_{7/2})^n$ *Nuclei*, A. L. Williams, M. Burlein, **G. R. Burleson, J. A. Faucett**, H. T. Fortune, E. Insko, R. Ivie, K. W. Johnson, G. P. Kahrimanis, J. A. McGill, C. F. Moore, C. L. Morris, D. S. Oakley, J. M. O'Donnell, D. Smith, and H. J. Ward.

5. *A study of Reaction* $^6Li(\pi^+,2p)$ *around the* $\Delta(1232)$ *Resonance Region*, D. Zhang, H. Breuer, N. S. Chant, B. S. Flanders, S. D. Hyman, M. A. Khandaker, D. J. Mack, P. G. Roos, J. D. Silk, **K. Dhuga, G. S. Kyle, M. Wang**, P.-A. Amaudruz, C. H. Q. Ingram, R. A. Schumacher, U. Sennhauser, J. Jacob, B. G. Ritchie, D. Rothenberger, J. McDonald, and D. A. Williams.

6. *Exclusive Two-Nucleon Absorption of Pions in* ^{16}O *and* ^{18}O *at 116 MeV*, R. A. Schumacher, P. A. Amaudruz, C. H. Q. Ingram, U. Sennhauser, H. Breuer, N. S. Chant, A. E. Feldman, B. S. Flanders, F. Khazaie, D. J. Mack, P. G. Roos, J. D. Silk, and **G. S. Kyle.**

At the Seventh International Conference on Polarization Phenomena in Nuclear Physics, Paris, France, July 9–13, 1990:

1. *Pion Elastic Scattering from Polarized* ^{13}C *in the Energy Region of the (3,3) Resonance*, Y. F. Yen, B. Brinkmöller, D. Dehnhard. S. M. Sterbenz, Yi-Ji Yu, **B. Berman, G. R. Burleson, K. Cranston, A. Klein G. S. Kyle**, R. Alarcon, T. Averett, J. R. Comfort, J. Görgen, B. Ritchie, J. Tinsley, G. W. Hoffmann, K. Johnson, M. Purcell, H. Ward, W. Williams, J. A. Faucett, S. J. Greene, J. Jarmer, J. A. McGill, C. L. Morris, S. Penttilä, N. Tanaka, H. T. Fortune, E. Insko, R. Ivie, J. M. O'Donnell, D. Smith, S. Høibråten, M. Khandaker, and S. Chakravarti. (Paper selected for oral presentation.)

2. *Asymmetry Measurements for the (π^+, π^0) Reaction of a Polarized ^{13}C Target*, J. Görgen, J. Comfort, T. Averett, J. DeKorse, B. Franklin, B. Ritchie, J. Tinsley, **G. Kyle, B. Berman, G. R. Burleson, K. Cranston, A. Klein**, J. A. Faucett, J. Jarmer, J. N. Knudson, S. Penttilä, N. Tanaka, B. Brinkmöller, D. Dehnhard, Y. F. Yen, H. Breuer, M. A. Khandaker, D. L. Naples, B. S. Flanders, D. Zhang, M. Barlett, G. W. Hoffmann, M. Purcell, and S. Høibråten. (Paper selected for oral presentation.)

3. *Polarization Asymmetries for the Reaction $\pi^- \vec{p} \rightarrow \pi^0 n$ at T_{π^-} =161 MeV*, J. Görgen, J. Comfort, T. Averett, J. DeKorse, B. Franklin, B. Ritchie, J. Tinsley, **G. Kyle, B. Berman, G. R. Burleson, K. Cranston, A. Klein**, J. A. Faucett, J. Jarmer, J. N. Knudson, S. Penttilä, N. Tanaka, B. Brinkmöller, D. Dehnhard, Y. F. Yen, H. Breuer, M. A. Khandaker, D. L. Naples, B. S. Flanders, D. Zhang, M. Barlett, G. W. Hoffmann, M. Purcell, and S. Høibråten. (Paper selected for oral presentation.)

4. *Measurements of the Spin Structure Function of the Nucleon*, The HERMES Collaboration: J. Amann, M. Arneodo, H. Baer, D. H. Beck, E. J. Beise, I. G. Bird, W. Brückner, **G. Burleson**, R. Carlini, K. Coulter, P. P. J. Delheij, G. Dodson, K. Dow, M. Düren, M. I. Ferreo, B. W. Filippone, S. J. Freedman, D. F. Geesaman, G. Graw, P. W. Green, L. G. Greeniaus, W. Haeberli, O. Häusser, R. Henderson, R. J. Holt, H. E. Jackson, E. Kabuss, E. Kinney, P. Kitching, **A. Klein**, W. Korsch, **G. Kyle**, R. Laszewski, W. Luck, B. Martin, S. Maeselli, J. McClelland, R. D. McKeown, C. A. Miller, R. Millner, J. Napolitano, D. Nowotny, C. N. Papanicolas, C. Peroni, K. Pitts, D. Potterveld, B. Povh, S. Price, R. Redwine, K. Rith, N. L. Rodning, P. Schiemenz, C. Scholz, A. Staiano, E. Steffens, N. Tanaka, V. van den Brand, M. Vetterli, H. Vogt, S. E. Williamson, T. Wise, R. Woloshyn, C. E. Woodward, L. Young, A. Zapfe, B. Zeidman, and P. Zetsche.

At the TRIUMF Pion Physics Workshop, TRIUMF, Vancouver, Canada, July 21, 1990:

1. *LADS Experiments—Quasielastic Scattering with CHAOS*, **G. S. Kyle**; invited paper.

At the LAMPF Users Group Meeting, Los Alamos, New Mexico, August 13–14, 1990:

1. *Pion Scattering from Polarized Nuclear Targets*, **G. R. Burleson**; invited paper.

At the Ninth International Symposium on High-Energy Spin-Physics, Bonn, Germany, September 10–15, 1990:

1. *Pion Elastic Scattering from Polarized ^{13}C in the Energy Region of the (3,3) Resonance*, Y. F. Yen, B. Brinkmöller, D. Dehnhard. S. M. Sterbenz, Yi-Ji Yu, **B. Berman, G. R. Burleson, K. Cranston, A. Klein G. S. Kyle**, R. Alarcon, T. Averett, J. R. Comfort, J. Görgen, B. Ritchie, J. Tinsley, G. W. Hoffmann, K. Johnson, M. Purcell, H. Ward, W. Williams, J. A. Faucett, S. J. Greene, J. Jarmer, J. A. McGill, C. L. Morris, S. Penttilä, N. Tanaka, H. T. Fortune, E. Insko, R. Ivie, J. M. O'Donnell, D. Smith, S. Høibråten, M. Khandaker, and S. Chakravarti.
2. *Proton Elastic Scattering from Polarized ^{23}C at 500 MeV*, G. Hoffman, M. Barlett, W. Kielhorn, G. Pauletta, L. Ray, J. Amann, J. Jarmer, K. Jones, S. Penttilä, N. Tanaka, **G. Burleson, J. Faucett**, M. Gilani, **G. Kyle, L. Stevens**, T. Mack, K. Mihailidis, D. Dehnhard, T. Averett, J. Comfort, J. Görgen, J. Tinsley, B. Clark, and S. Hama.

4 Advanced Degrees Awarded

During the period of this Progress Report, the following students were awarded Ph.D. degrees:

1. **Mohini Wahman Rawool**, 1988. Thesis title: *The Measurement of the Spin Correlation Parameters C_{SL} and C_{LL} in $\vec{n}\vec{p} \rightarrow np$ Scattering at Energies 484, 634, and 788 MeV.*
2. **Robert William Garnett**, 1989. Thesis title: *Measurement of np Elastic Scattering Spin-Spin Correlation Parameters at 484, 634, and 788 MeV.*
3. **Michael Ervin Beddo**, 1990. Thesis title: *A Measurement of $\Delta\sigma_L(np)$, the Difference Between Neutron-Proton Total Cross Sections in Pure Longitudinal Spin States.*

5 Personnel

The effort that has been devoted to this grant by those supported by it, from April 1, 1988, through March 31, 1991, (projected) is given below. We note that during this time two graduate students, Mohini Rawool and Robert Garnett, were supported by Argonne National Laboratory and Los Alamos National Laboratory.

Faculty Members:

George R. Burleson, 18 man-months

Gary S. Kyle, 18 man-months

Postdoctoral Research Associates:

John Faucett, 7 man-months

Andreas Klein, 22 man-months

Sanjoy Mukhopadhyay, 29 man-months

Mohini Rawool-Sullivan, 5 man-months

Graduate Students:

Michael Beddo, 27 man-months

Ming Hong Wang, 36 man-months

Kevin Cranston, 9 man-months

Maher El-Ghossain, 10 man-months

Qihua Zhao, 3 man-months

James Stevens, 3 man-months

Undergraduate Student:

Brian Berman, 3 man-months

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