PION- AND PROTON-NUCLEUS INTERACTIONS AT INTERMEDIATE ENERGY

Progress Report
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SUMMARY

We report on scattering and reaction experiments on light nuclei using the π -meson and proton beams from the Los Alamos Meson Physics Facility (LAMPF) and the Indiana University Cyclotron Facility (IUCF). Differential cross sections, cross section asymmetries, and angular correlation functions have been measured in order to test models of the reaction mechanism and of nuclear structure.

At LAMPF we have measured asymmetries for pion scattering from polarized ^{13}C which are uniquely sensitive to the isoscalar spin density. In order to determine details of the reaction mechanism, we have obtained approval for a scattering experiment on polarized ^3He for which the nuclear structure is very well known. Once the reaction mechanism is better understood we will be able to extract the information on the spin density contained in the ^{13}C asymmetry data. In preparation for the ^3He experiment, we have shown in a test run that events from elastic scattering on the ^3He gas can be distinguished from a large background of events originating in the glass wall of the target cell.

We have completed data taking for two studies of elastic scattering of π^+ from ^6Li and ^{13}C . The detailed differential cross sections from these experiments will be used to constrain theoretical analyses of previous polarization experiments done at the Pierre-Scherrer-Institute (PSI) and at LAMPF.

We have analyzed π -triton coincidence events from the $^4\text{He}(\pi, \pi' t)p$ reaction and have found evidence for direct triton knockout from ^4He . We have extended these angular correlation measurements to higher energies and to ^2H and ^3He targets. Preliminary analysis of the new $^2\text{H}(\pi, \pi' p)n$ data shows anomalously large π^+p/π^-p ratios at incident energies near the P_{33} π -nucleon resonance, even for the case of proton knockout from the weakly bound ^2H .

At IUCF we have performed the first $^4\text{He}(p, n)$ experiment at intermediate energies, $T_p = 100, 147,$ and 200 MeV, in a search for previously reported narrow states in ^4Li of widths of ≈ 1 MeV. Within the statistics of the data we have found no evidence for such narrow structures. The $^4\text{He}(p, n)$ cross sections at 100 MeV are nearly finalized and the replay of data for ^3He and $^4\text{He}(p, n)$ at 147 MeV and 200 MeV has begun.

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1 Introduction

This progress report describes the work done between June 1, 1990 and May 31, 1993 under contract No. DOE/DE-FG02-87ER40362 between the University of Minnesota and the United States Department of Energy.

The experimental research was performed at the Los Alamos Meson Physics Facility (LAMPF) and the Indiana University Cyclotron Facility (IUCF). The preparation for the experiments and the data taking and analysis were done together with colleagues from the Los Alamos National Laboratory, New Mexico State University, Tri-University Meson Facility (TRIUMF), Arizona State University, and the Universities of Indiana, Texas, Maryland, Pennsylvania, and Colorado. We especially acknowledge the continuing collaboration with Dr. C. L. Morris of Los Alamos National Laboratory. We also appreciate very much the collaboration and discussions with nuclear theorists: Prof. W. R. Gibbs of New Mexico State University and Los Alamos National Laboratory, Prof. D. Ernst of Texas A&M University, and Prof. P. J. Ellis of the University of Minnesota.

The efforts of the following personnel, supported by this contract, were essential in performing the experiments and in their analysis: Dr. B. Brinkmüller, Dr. J. L. Langenbrunner and Dr. M. Palarczyk as full-time Research Associates, Dr. M. A. Franey as part-time Research Associate, and four graduate students, C. M. Edwards, M. A. Espy, Yi-Fen Yen, Yi-Ju Yu, and P. Yurek. Prof. S. Chakravarti of California Polytechnic University at Pomona collaborated with us on the theoretical analysis of the polarization experiment during visits at the University of Minnesota and Los Alamos National Laboratory.

The work in progress is discussed in section 2, completed work is presented in section 3, publications, etc. are listed in section 4. Figures and references may be found at the end of each subsection, e.g. 2.1. A summary of this report is presented on page 1.

2 Work in Progress

2.1 ${}^4\text{He}(\vec{p},n){}^4\text{Li}$ reaction at 100, 147, and 200 MeV (IUCF Exp. 342 and 342U)

Spokespersons: M. A. Palarczyk (UofM), B. Brinkmüller (U Karlsruhe), D. Dehnhard (UofM), and L. C. Bland (IUCF); Participants: C. M. Edwards, J. L. Langenbrunner, M. A. Espy (UofM), D. Carman (IUCF).

2.1.1 Introduction

In April of 1991 we performed the first (p,n) experiment on ${}^4\text{He}$ at intermediate energies. The experiment was done at the Neutron-Time-Of-Flight Facility (NTOF) at the Indiana University Cyclotron Facility (IUCF). Supplementary data were taken in June of 1992 at IUCF. This experiment is the Ph. D. thesis experiment of Carla M. Edwards.

The primary goal of the experiment is the investigation of the ${}^4\text{He}(\vec{p},n){}^4\text{Li}$ reaction over a range of incident proton energies where the relative strengths of the spin-dependent and spin-independent isovector nucleon-nucleus forces change significantly. Since (p,n) reactions involve the transfer of one unit of isospin, the isovector components of the nucleon-nucleon interaction are effectively isolated.

In addition to these nuclear physics aspects of our work, the cross sections of the ${}^4\text{He}(p,n){}^4\text{Li}$ reaction are of importance in astrophysics[Bi90]. Models of mass accretion of neutron stars, of solar flares, etc., require knowledge of the ${}^4\text{He}(p,n){}^4\text{Li}$ continuum spectra. For lack of experimental data, current theories of these processes have to resort to theoretically predicted cross sections using a semiclassical model[Bi90]. Our experiment provides the needed spectra and thus eliminates the need of model calculations for this reaction

Fig. 1 shows a plot of the square of the ratio of the spin-dependent isovector part of the nucleon-nucleon t -matrix to the spin-independent isovector part as a function of energy at zero momentum transfer [Lo81]. Qualitatively similar results hold for larger momentum transfers. This ratio indicates the relative sensitivity of the (p,n) reaction to spin-transfer ($\Delta S = 1$) versus no-spin-transfer ($\Delta S = 0$) modes of excitation. One can see that the $\Delta S = 1$

excitations should be relatively stronger than the $\Delta S = 0$ excitations as the proton energy is increased from 100 to 200 MeV, which is the energy range of this experiment. Specifically, the transition to the $J^\pi = 2^-$ ground state of ${}^4\text{Li}$, which can be reached only by $\Delta S = 1$, should become more prominent at 147 and 200 MeV, whereas the transition to the 1^- first-excited state is expected to be weaker than at 100 MeV, because it involves primarily $\Delta S = 0$ if it is mostly a ${}^1\text{P}$ state.

This strong energy dependence should aid in determining the contributions from excitations of different multipolarities to the continuum spectra of ${}^4\text{Li}$. The ${}^4\text{He}(\vec{p},n)$ reaction, therefore, will provide new information on the isovector excitations of mass-4 nuclei, and about the parameters of levels in ${}^4\text{Li}$ which have been quite controversial recently. Previous work on mass-4 nuclei [Ha92, To65, To66, Br90a, Br90b] has reported widths of the ground and first-excited states of between 1 and 7 MeV and resonance energies which differ by more than 1 MeV. These level parameters are summarized in the table below.

^4Li Resonance Energies Above $p+^3\text{He}$ Threshold (E_r) and Widths (Γ)								
	$J^\pi = 2^-$ g.s.		$J^\pi = 1^-$ (^3P)		$J^\pi = 0^-$		$J^\pi = 1^-$ (^1P)	
	E_r	Γ	E_r	Γ	E_r	Γ	E_r	Γ
	(MeV)	(MeV)	(MeV)	(MeV)	(MeV)	(MeV)	(MeV)	(MeV)
[Ha92]	4.07	6.03	4.39	7.35	6.15	9.35	6.92	13.51
[To65, To66]	4.74	≈ 5.5	6.15	≈ 5.5				
[Br90a]	3.3	≈ 1.0	5.9	≈ 1.5				
[Br90b]	3.3	0.8						

Tombrello [To65, To66] and Brinkmüller *et al.* [Br90a] both quote reduced widths, γ^2 , where $\gamma^2 = \Gamma/2P_c$ and P_c is the penetrability of ${}^3\text{He}$ for protons of the appropriate energy. For the present case of very wide states near breakup threshold, $\gamma^2 \approx \Gamma$.

An R -matrix analysis of $p+{}^3\text{He}$ data by Hale [Ha92] resulted in widths of $\Gamma > 6$ MeV for the four lowest-lying states in ${}^4\text{Li}$. Previous phase shift analyses of $p+{}^3\text{He}$ and $n+T$ elastic scattering data by Tombrello [To65, To66], while disagreeing with Hale's level energies by up to nearly 2 MeV, found similarly large widths. However, the experimental widths extracted from three-body decay spectra by Brinkmüller *et al.* [Br90a] and by Bruno *et al.* [Br90b] were

found to be of the order of 1 MeV, and the resonance energies differ by more than 1 MeV from the R -matrix and phase-shift analyses.

The ${}^4\text{He}(n,p){}^4\text{H}$ reaction has been studied [Me67] at $T_p = 152$ MeV. No evidence for narrow structures could be seen in the spectra from that reaction, which excites the analog states of the states in ${}^4\text{Li}$, because the energy resolution was 10 MeV. A broad structure of about 20-MeV width was found at a missing mass of 29 ± 3 MeV and interpreted as due to the excitation of the giant dipole levels. The energy resolution in the current (p,n) experiment is generally better than 1 MeV.

The complications of three-body phase space and kinematics inherent in the three-body decay experiments and theoretical analyses cited above are avoided in the present experiment, since the inclusive neutron spectra were measured. In addition, the energy resolution in this experiment is an order of magnitude better than the (n,p) work. The data from this experiment, therefore, should allow a determination of the resonance energies and widths of states in ${}^4\text{Li}$, provided there are any narrow structures, and should resolve the controversy.

2.1.2 Experiment

Neutron time-of-flight spectra, from which the excitation energy spectrum of ${}^4\text{Li}$ may be constructed, were measured simultaneously at two fixed neutron detector stations, one located at a distance of 75.4 m from the target at a nominal scattering angle of 0° , the other at a distance of 49.0 m, nominally at 24° . Six NE102 plastic scintillation detectors, of dimensions 10 cm $\times$ 15 cm $\times$ 100 cm, were positioned in a vertical stack in each detector station. These detectors were oriented so that their long axes were parallel to the neutron flux, and were viewed by a pair of photomultiplier tubes placed at each end of each detector. This orientation provides superior energy resolution and detection efficiency.

By changing its magnetic field, the “beam swinger” at the IUCF NTOF Facility changes the direction of the incident proton beam between 0° and 20° , allowing measurements at scattering angles θ_{lab} between 0° and 20° at the 0° detector station and between 24° and 44° at the 24° detector station. Time-of-flight spectra were taken both with proton spin up and down (with respect to the reaction plane) at scattering angles between 0° and 44°

in approximately 5° steps at three proton energies: 100, 147, and 200 MeV. The proton spin was flipped rapidly relative to the length of the runs to minimize systematic differences between the spin-up and spin-down spectra.

A high-pressure, low-temperature, gas target was developed for this experiment. The target cell is a welded stainless steel box with 25 μm thick Havar entrance and exit windows separated by about 4.8 cm. The cell was mounted on a vacuum feedthrough pushrod, which enabled the placement of the cell immediately downstream from the pivot point of the beam swinger; a (retractable) solid target ladder was located at the pivot point. This arrangement allowed measurements with either solid targets (required for beam setup and calibrations) or gaseous targets without breaking vacuum.

Because the target cell was positioned about 6 cm downstream from the pivot point of the beam swinger, changing the beam angle caused the position of the beam spot on the target to change. The Havar windows, therefore, were designed with a rectangular shape (1.6 cm high by 4.6 cm wide) to accommodate beam angle changes of up to 24° . The windows were also designed to permit an 8-mm clearance for the beam and its halo at all angles. The bursting pressure of Havar windows of these dimensions is about 10.6 kT at room temperature and is known to increase at lower temperatures.

In order to achieve a high ratio of scattering centers in the gas to those in the windows, the target cell was operated near liquid nitrogen temperatures. Cooling was provided by a continuous flow of liquid nitrogen through copper tubing which was in thermal contact with copper plates attached above and below the cell. When filled with helium, the cell was safely operated at a pressure of 5.5 kT and a temperature of about 110 K. This provided a ratio of scattering centers in the gas to those in the windows of 5 to 1 for ^4He , which assured a good signal-to-background ratio.

Examples of full- and empty-target spectra are shown in Fig. 2 as a function of missing mass (MM) assuming $^4\text{He}(p,n)$ kinematics with $\text{MM} = 0$ at the $p + ^3\text{He}$ threshold. At small scattering angles (See the top half of Fig. 2 for spectra at $\theta_{\text{lab}} = 0^\circ$ and $T_p = 100$ MeV), there are prominent peaks at negative missing mass due to isobaric analog transitions and the excitation of Gamow-Teller resonances in the nuclei comprising Havar. The spectrum

from the ${}^4\text{He}(p,n){}^4\text{Li}$ reaction is seen at positive missing mass, where the spectrum from reactions on Havar is featureless. At larger angles (see, for example, the spectra at $\theta_{\text{lab}} = 24^\circ$ and $T_p = 100$ MeV in the bottom half of Fig. 2), the signal-to-background ratio is even more favorable because the reactions on Havar become less important and the ${}^4\text{He}(p,n)$ cross section has a maximum near $\theta_{\text{lab}} = 20^\circ$ between 100 and 200 MeV.

At all angles and energies, spectra were taken with an empty target for background subtraction, and with ${}^{12}\text{C}$ and ${}^{13}\text{C}$ foils for relative neutron detection efficiency and energy calibrations. A few spectra were also measured with methane (enriched in ${}^{13}\text{C}$) in the target cell to look for possible systematic differences between spectra from solid and gaseous targets.

2.1.3 Results

The analysis of the $T_p = 100$ MeV data is nearly complete. The relative carbon yields compare well to previously published values, and the solid ${}^{13}\text{C}$ spectra compare well to the ${}^{13}\text{C}$ -enriched methane spectra. The quality of the solid and gaseous carbon data implies a similar quality in the helium data.

The double-differential cross sections $d^2\sigma/d\Omega/dE$ in the laboratory system, obtained by subtracting normalized empty-target spectra, are shown in Fig. 3 for all angles at $T_p = 100$ MeV. These spectra have been corrected for neutron attenuation through the charged-particle degrader and the column of air in the neutron flight path. The relative neutron detection efficiencies were determined as a function of neutron energy for proton energies 100, 147, and 200 MeV by comparing the ${}^{12,13}\text{C}(p,n)$ yields of this experiment and previously measured cross sections [Kn80, Ra81, Ta82, Oh86, Ta87]. Within the statistics of the ${}^4\text{He}(p,n)$ spectra, there is no evidence of structures of 1 MeV width as deduced from the three-body decay experiments of Brinkmüller [Br90a] and Bruno [Br90b].

The double-differential cross sections from the spin-sorted 100-MeV spectra, to which the same corrections were applied as described above, may be seen in Fig. 4. These spin-sorted cross section spectra should highlight any spin-dependent processes, but again there is no obvious evidence of narrow structures within statistics.

Angular distributions of the $T_p = 100$ MeV differential cross sections $d\sigma/d\Omega$ and ana-

lyzing powers A_y are shown in Fig. 5 for the 0 to 8 MeV bite in ^4Li missing mass. DWIA calculations were done for each of the four lowest-lying states ($J^\pi = 2^-, 1^- (^3\text{P}), 0^-,$ and $1^- (^1\text{P})$) as predicted by Hale [Ha92]. Harmonic oscillator wave functions, shell model orbitals, the optical potential of van Oers *et al.* [Va82] without his “exchange” term, and the nucleon-nucleon forces of Franey and Love [Fr85] were used. The calculated cross sections and analyzing powers for each state were then added together in the approximate strengths in which these states are expected to contribute within the 0–8 MeV range in missing mass. Each curve in Fig. 5 represents these summed calculations assuming different values of the oscillator parameter, b . An oscillator parameter of $b = 1.2$ fm reproduces the r.m.s. charge radius of ^4He , but a somewhat larger value is expected to give a more accurate wave function of ^4Li . A larger oscillator parameter also better describes the angular dependence of the measured cross sections, although the angular dependence of the calculations does not match that of the measurements very well in general. The summed DWIA cross sections were multiplied by a factor of $\frac{1}{2}$ to better agree with the magnitude of the measured cross sections, indicating that roughly $\frac{1}{2}$ of the single-particle model strength is seen. Our DWIA calculations do not explicitly include the quasi-free neutron knock-out process which is expected to contribute to the neutron spectra. Its inclusion would thus reduce the fraction of single-particle strength deduced above. The transition densities from the harmonic oscillator wave functions do not have the proper recoil corrections. Thus our calculations should be considered only a first step in the analysis of the data. In the near future we plan to use (in the DWIA calculations) the wave functions of the recoil corrected continuum shell model (RCCSM) which were recently made available to us by D. Halderson.

The neutron spectra taken at $T_p = 147$ and 200 MeV in 1991 contained narrow structures in a small range of scattering angles (10° – 20°) with strong positive analyzing powers. These structures appeared at approximately the same missing mass with approximately the same widths as the ones extracted from the previous work on three-body decay reactions [Br90a, Br90b]. Such structures were also seen in a couple of neutron spectra from the $^3\text{He}(\vec{p}, n)$ reaction. (See sec. 2.2). After considerable effort in analyzing the data, however, these peaks were found to be due to protons which elastically scattered from the target nuclei and escaped

through the beam swinger's dump magnet.

Because the spectra at 147 and 200 MeV contained these anomalous peaks, and because clean spectra are necessary to confidently draw conclusions about the existence of narrow structures in ${}^4\text{Li}$, new ${}^4\text{He}(\vec{p},n)$ spectra and a complete set of ${}^3\text{He}(\vec{p},n)$ spectra were taken in June 1992 at IUCF in collaboration with B. A. Anderson, J. W. Watson, R. Madey, and Y. Wang of Kent State University. In order to minimize the amount of dirt in the spectra, the shielding in the swinger area was improved and a energy degrader for charged particles was installed in the 0° flight path. Consequently, the new spectra, which are currently in the early stages of analysis, are free of charged-particle contamination. Online analysis suggests that these data, like those at 100 MeV, do not support the existence of narrow states in ${}^4\text{Li}$. A brief discussion of the on-line spectra from ${}^3\text{He}(\vec{p},n)$ is presented in Sec. 2.2 (without figures).

2.1.4 Conclusions

Within the statistics of the 100 MeV ${}^4\text{He}(\vec{p},n)$ data, there is no evidence of narrow states in ${}^4\text{Li}$. This conclusion is supported by the online spectra taken at 147 and 200 MeV during Exp. 342U.

A simple DWIA analysis of the 100 MeV-data using harmonic oscillator wave functions indicates that about $\frac{1}{2}$ of the single-particle model strength is observed. For further analysis, we will use the RCCSM wave functions which properly account for recoil and the unbound nature of the states in ${}^4\text{Li}$. In the RCCSM both quasi-free scattering and inelastic scattering to excited states are included, although these contributions cannot be separated. The transition amplitudes, however, are given for the individual multipole components, which contribute to the continuum of ${}^4\text{Li}$ states with different strengths at different excitation energies (missing masses).

The strong energy dependence of the relative strengths of the spin-dependent and spin-independent isovector parts of the nucleon-nucleon force in the energy range of this experiment results in a strong energy dependence of the shapes of the measured cross section spectra. The data from the ${}^4\text{He}(\vec{p},n)$ reaction at three proton energies will provide a test of

the RCCSM wave functions and thus of the forces and approximations applied in that model. The data of this work will also be used in astrophysical models of, for example, accreting neutron stars[Bi90].

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Fig. 1. Square of the ratio of the spin-dependent isovector part of the nucleon-nucleon t -matrix to the spin-independent isovector part as a function of energy at zero momentum transfer [Lo81]. The proton energies at which ${}^4\text{He}(p,n)$ spectra were taken are indicated by the dashed vertical lines.

Fig. 2. Missing mass spectra at $T_p = 100$ MeV for $\theta_{\text{lab}} = 0^\circ$ (top) and 24° (bottom) obtained from the target cell filled with ${}^4\text{He}$, overlaid with the spectra from the empty cell. The Gamow-Teller resonances and isobaric analog transitions from (p,n) reactions on the components of Havar are clearly visible at negative missing mass in the 0° spectra, whereas the 24° Havar spectrum is relatively featureless.

Fig. 3. Spin-unsorted missing mass spectra for $^4\text{He}(\vec{p},n)^4\text{Li}$ at $T_p = 100$ MeV at all angles. There is no evidence for narrow structures in ^4Li within the statistics of these data.

Fig. 4. Spin-up (shaded histograms) and spin-down (unshaded histograms) missing mass spectra for ${}^4\text{He}(\bar{\text{p}},\text{n}){}^4\text{Li}$ at $T_p = 100$ MeV at all angles. There is no evidence for narrow structures in ${}^4\text{Li}$ within the statistics of these data.

Fig. 5. Angular distributions for $d\sigma/d\Omega$ (top) and A_y (bottom) for ${}^4\text{He}(p,n){}^4\text{Li}$ at $T_p = 100$ MeV for the 0–8 MeV bite in missing mass. The different curves are the sum of the DWIA predictions for the four lowest-lying states in ${}^4\text{Li}$ assuming different oscillator parameters, b .

2.2 $^3\text{He}(\vec{p},n)$ Reaction at 147 and 200 MeV (IUCF Exp. 342U).

Spokesman and participants as for section 2.1. This phase of the experiment was done in collaboration with B. Anderson, J. Watson, R. Madey, and Y. Wang of Kent State U.

During the course of IUCF Exp. 342 some narrow peaks were seen (at a few selected forward angles) in the neutron spectra from the (p,n) reaction on the ^4He -gas filled cell. In order to identify the source of these peaks we decided to take some spectra at $T_p = 200$ MeV with ^3He in the target cell. For $^4\text{He}(p,n)$ such structures were not completely unexpected since the work of Ref.[Br90a] and Ref.[Br90b] had provided evidence for about 1-MeV wide states in ^4Li . No evidence for narrow states had ever been reported for the three-proton system[Ti87], so no peaks were expected from the $^3\text{He}(p,n)3p$ reaction. However, with ^3He gas in the cell we also observed peaks at the same angles as for ^4He . This observation led to the identification of the narrow peaks as due to elastically scattered protons which, at 147 MeV and 200 MeV, were energetic enough to reach the 0° neutron detector station, where we had relied on a sweeping magnet and suitable shielding to remove all charged particles. As mentioned in Sec. 2.1, better shielding and an energy degrader in the path to the 0° hut removed all charged particles from the neutron spectra in Exp. 342U.

For Exp. 342U, the $^3\text{He}(\vec{p},n)$ reaction had been proposed as a parallel study to that of the $^4\text{He}(\vec{p},n)$ reaction. Spectra at 0° , 5° , 10° , 16° and 20° (and at 24° , 29° , 34° , 40° , and 44°) were taken with the two neutron huts nominally at 0° and 24° . As for the ^4He part of the experiment, the measurements were done at $T_p = 147$ MeV and 200 MeV.

The $^3\text{He}(p,n)3p$ reaction leads to an unbound system of one neutron and three protons. No resonant states have ever been seen for the three-proton system[Ti87]. However, the spectra of the $^3\text{He}(p,n)3p$ reaction at the lower incident energy, $T_p = 25$ MeV, showed evidence[Ba69] for a final-state interaction (FSI) in the two-proton system. The two-proton system undergoes FSI in the 1S_0 state centered at about 20 MeV/c relative momentum[Wa52]. The neutron spectra would be affected by this FSI but it may not be sufficiently strong to cause a peak. Nevertheless, the simple four-body phase space spectra would be altered by the FSI, an effect that would be most pronounced near the three-proton threshold. Except for the

region near threshold, the spectra are expected to be dominated by quasi-free scattering. Since quasi-free scattering is probably also contributing to the neutron spectra from the reaction on ^4He , the data taken on ^3He should aid in the analysis of the data for $^4\text{He}(p,n)^4\text{Li}$.

As expected, no structures were seen in the on-line neutron spectra. It appears that the spectra from ^3He at angles larger than $\theta_{lab} = 0^\circ$ are dominated by the quasi-free process. At $\theta_{lab} = 0^\circ$ the $^3\text{He}(p,n)$ reaction is suppressed by the Pauli exclusion principle which forbids $L=0$ scattering to the region of missing mass (MM) near the three-proton breakup threshold. Indeed, the on-line spectra at $\theta_{lab} = 0^\circ$ contain only a small yield consistent with background in the region of MM at both incident energies. The spectra at the other angles show a broad bump centered at a MM which increases with angle, following roughly the free N-N kinematics.

This experiment made the first measurement of neutron spectra from the $^3\text{He}(p,n)$ reaction at intermediate energy. The data are currently being analyzed to obtain the double-differential cross sections $d^2\sigma/d\Omega dE$. They will be compared to predictions of quasi-free scattering models. Comparisons with simple four-body phase-space spectra might yield evidence for FSI.

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2.3 $(\pi^\pm, \pi^{\pm'} x)$ reaction on ^2H , ^3He , and ^4He (LAMPF Exp. 1216)

Spokespersons: J. Langenbrunner (UofM), M. K. Jones (Rutgers) and D. Dehnhard (UofM);
 Participants: M. Palarczyk, M. A. Espy, C. M. Edwards, P. D. Yurek (UofM), C. R. Whitley, K. Jones, J. Johnson, C. F. Moore (U Texas), J. D. Zumbro, C. L. Morris, R. M. Whitton, M. Rawool-Sullivan, J. M. O'Donnell (Los Alamos), B. K. Park (NMSU), B. J. Kriss (Colorado), K. Maeda (Tohoku).

Exclusive $(\pi^\pm, \pi^{\pm'} x)$ experiments on the few-body nuclei ^2H , ^3He , and ^4He are motivated in part by the observation of surprisingly large cross section ratios $R = \frac{\sigma(\pi^+, \pi^{+'} p)}{\sigma(\pi^-, \pi^{-'} p)}$ for ^4He and ^{16}O targets. Whereas the inclusive (inelastic) cross sections give a ratio of $r = \frac{\sigma(\pi^+, \pi^{+'})}{\sigma(\pi^-, \pi^{-'})}$ of $\cong 1$ as a consequence of charge symmetry, the exclusive reaction ratio R was found to be ≥ 25 in the region of nuclear excitation energy near 30 MeV[1]. This contrasts to the expected value of 9 if the $(\pi^\pm, \pi^{\pm'} p)$ reaction were to proceed exclusively by quasi-elastic π -proton scattering near the P_{33} pion-nucleon resonance. (The ratio of π^+ -proton to π^- -proton elastic scattering amplitudes is 3 for the P_{33} resonance.) The current literature has three different reaction models which attempt to describe the data. All of these invoke interference between two or more reaction amplitudes to describe deviations from the free pion-nucleon ratio.

This group (Ref. 1) put forward the possibility that nuclear structure effects of ^4He in the region between 24 MeV and 30 MeV of nuclear excitation (where the giant dipole resonance is thought to be important) would interfere with the direct-knockout mechanism. If the reaction $(\pi, \pi' p)$ proceeds only via the formation and decay of a state of good isospin, the ratio R would be near one, but moreover, this reaction amplitude may interfere with direct-knockout.)

This group (Ref. 2) also uncovered the first evidence for a reaction amplitude whereby the pion directly couples to a triton in a cluster model of the ^4He wavefunction. A model authored by W. R. Gibbs (LANL) was used in Ref. 2 which calculated angular correlation functions using the equation:

$$\frac{d^3\sigma}{d\Omega_\pi d\Omega_p dk'_\pi} = |\phi(k_t) f_{\pi p}(\mathbf{k}_\pi, -\mathbf{k}_t, \mathbf{k}'_\pi, \mathbf{k}_p) + \phi(k_p) f_{\pi t}(\mathbf{k}_\pi, -\mathbf{k}_p, \mathbf{k}'_\pi, \mathbf{k}_t)|^2 k_p^2 \frac{dk_p}{dk'_\pi}. \quad (1)$$

The function $\phi(k)$ is a momentum-space wave function of the $p + t$ system. The momenta

$\mathbf{k}_t$, $\mathbf{k}_p$, $\mathbf{k}_\pi$ were determined in this exclusive experiment by measuring $\mathbf{k}_\pi$ and $\mathbf{k}_t$ or $\mathbf{k}_p$ and using momentum conservation. In $f_{\pi p}$, $-\mathbf{k}_t$ is the momentum of the proton before and $\mathbf{k}_p$ is the momentum of the proton after the collision. In $f_{\pi t}$, $-\mathbf{k}_p$ is the momentum of the triton before and $\mathbf{k}_t$ is the momentum of the triton after the collision. We will apply a similar model (based on Eq. 1) to the data from the current experiment.

The $^{16}\text{O}(\pi^\pm, \pi^\pm' p)$ reaction studied by Kyle *et al.* [3] also showed very large cross section ratios. Takaki and Thies [4] have attempted to interpret these data in the framework of the Δ -hole model. In that model, an amplitude from Δ -induced proton knockout interferes with the quasi-free pion-induced proton knockout. This is an example of a “medium effect” on the pion-nucleon interaction.

We measured π -proton coincidence spectra both with π^+ and π^- for ^2H and ^3He , the simplest few-body nuclei, where much progress has been made recently in the quantitative understanding of the nuclear wave functions [5]. We also decided to take additional data on ^4He in order to supplement the data set of Ref. 1. We are now extracting the angular correlation functions. With this experiment, we expect to minimize the effects due to structure while providing different nuclei for which the reaction mechanism could be studied. Structure effects are expected to be negligible in the case of scattering from deuterium and should be minimal for scattering from ^3He .

The previous coincidence experiment [1] at LAMPF, with ^4He as a target, was done using the Energetic Pion Channel and Spectrometer system (EPICS) [6] and fast plastic scintillators for recoil particle detection and identification. During the summer of 1992 we have taken data in the P^3 channel at LAMPF using the Large Acceptance Spectrometer (LAS) and CsI-phoswich recoil particle detectors which we have developed with colleagues in Los Alamos [7]. The present data emphasize the region of low momentum transfer, where the previous data of Jones [1] and Kyle [3] show the very interesting effects in the cross section ratio. Most of the data of Kyle *et al.* are for large momentum transfers between $q \approx 1.6 \text{ fm}^{-1}$ and 2.6 fm^{-1} . Large deviations between the data and the model predictions of Takaki and Thies [4] exist for the scattering angle of $\theta_\pi^{lab} = 35^\circ$ where the momentum transfers of the experiments of Ref. 1, Ref. 3 and the present one are similar ($q \approx 1 \text{ fm}^{-1}$).

In order to be able to perform this experiment, it was necessary to shield the recoil detectors from muons. A computer program was written to calculate the flux of muons through a recoil particle detector due to the decay of a beam pions into muons [8]. With this program, we calculated the most forward angle and the closest distance that a detector could be placed and avoid the muon cone. We procured tungsten (two pieces of dimension 8 in. $\times$ 3 in. $\times$ 1 in.) for muon shielding. The tungsten (density 19.3 g/cm³) shielded the forward detectors more effectively than lead (density 11.35 g/cm³), given the restrictions on space for our setup.

We developed a CsI-phoswich detector (dimension 3 in. $\times$ 3 in. $\times$ 2.5 in.) for the identification of the charged particles x (where $x = p, d, t, \dots$). Protons, deuterons, and tritons, with respective momenta in the ratio of 1:2:3, give responses in about that ratio in a thin plastic scintillator. We have coupled one side of the 2.5-inch thick CsI crystal to a thin plastic scintillator and the other side to the photomultiplier tube. Incident charged particles of a certain energy range first pass the plastic scintillator and then stop in the CsI crystal.

The working principle of phoswich detectors is based on the use of two scintillators with different decay times viewed by a single compatible photomultiplier. The CsI-phoswich detector allows particle identification because the fast light output of the plastic scintillator (which is approximately proportional to energy loss) is largely separable from the relatively slower response of the CsI which measures the residual energy. The first CsI-phoswich detector was described by some of us in Ref. [7]. We have improved upon that detector for this experiment by using the fast response of a plastic scintillator (Bicron 404) which we separate from the "relatively fast" component of the CsI. These detectors were tested in the Test Channel at LAMPF, where it was shown that they could be used in Exp. 1216. This detector is the fastest phoswich detector that we know of, and is about eight times faster than the original CsI-phoswich detector.

Six such CsI-phoswich recoil particle detectors were mounted in the reaction plane on an aluminum stand which was connected to the scattering chamber such that it had about 60° rotational freedom with respect to the pion spectrometer. Experimental conditions for the recoil detectors, the cooled-gas target and the LAS were kept as similar as possible for

π^+ and π^- so that the ratio of these cross sections for particle knock-out could be reliably extracted.

The particle-dependent pulse height from the plastic scintillators and the particle's time of flight allowed identification and determination of the energy of knocked-out particles. In Fig. 1 we demonstrate the time-of-flight (TOF) spectra of the knocked-out (x) particles with π^+ and π^- incident at $T_\pi = 240$ MeV on the deuterium gas target. It is clear from this figure that the yield for proton-knockout from deuterium (TOF between 4 and 5 ns) is much larger with π^+ than with π^- . These figures are based on the raw spectra and have not been normalized to integrated beam. Note however, that the events near 10 ns can be used for an online normalization because they are primarily from π -deuterium elastic scattering. Relative yields for elastic scattering should be equal for π^+ and π^- because of charge symmetry.

In Fig. 2 we illustrate the pulse-height spectra of the CsI-phoswich for the π^+ -induced knock-out particles shown in the TOF spectrum (Fig. 1). The light output integrated for the first 30 ns is the ordinate and the light output integrated for the subsequent 100 ns is the abscissa. Using this information, coupled with information from the scattered pion using LAS, three-body final states are kinematically determined. In Fig. 2 events clustered around the point near Short Gate = 125, and Long Gate = 200 (both in arbitrary units), are quasi-free knockout protons that pass the plastic and the CsI. Events with Short Gate = Long Gate = 50 are mostly deuterons which are stopped in the plastic scintillator.

Exp. 1216 was given about 50% of the PAC-approved integrated pion flux during the last run cycle. The proposal called for 28 combinations of target (^2H , ^3He , ^4He), angle (between 20° to 90°) and incident energy (180, 240, 300 MeV). Table I lists the target, the incident pion energy, the angle of the scattered pion (primarily low momentum transfer) at which data were taken, that is, at a total of 14 combinations. This is about one-half of the proposed data. (Some inclusive data (π^+ only) were taken at 500 MeV). We hope to continue this program at LAMPF in the future.

Table II gives some preliminary results for the ratio $R = \frac{\sigma(\pi^+, \pi^+ p)}{\sigma(\pi^-, \pi^- p)}$ for $^2\text{H}(\pi, \pi p)$ at the quasifree knockout angle. We found proton knockout cross section ratios R that differ

Table I: Combinations of target, incident energy, and pion scattering angle for which data were taken. $E_x^{q.f.}$ are the nuclear excitation energies corresponding to quasifree proton-knockout.

Target Nucleus	T_π (MeV)	θ_π^{lab} (deg)	$E_x^{q.f.}(\pi, \pi' p)$ (MeV)
^2H	180	40°	12
^3He	180	40°	18
^4He	180	40°	34
^2H	210	35°	12
^3He	220	45°	26
^2H	240	32°	12
^3He	240	32°	18
^4He	240	32°	34
^2H	300	$27^\circ, 44^\circ$	12, 25
^3He	300	$27^\circ, 44^\circ$	18, 34
^4He	300	$27^\circ, 44^\circ$	34, 53
^4He	500	50°	(π^+ inclusive)

Table II: Preliminary results for the ratio $R = \frac{\sigma(\pi^+, \pi^{+'} p)}{\sigma(\pi^-, \pi^{-'} p)}$ with the deuterium gas target. The momentum transfer q , and statistical uncertainties are given for R .

T_π (MeV)	θ_π^{lab} (deg)	q (fm $^{-1}$)	R
180	40°	0.95	17.8 ± 1.4
210	35°	0.95	19.3 ± 1.7
240	32°	0.95	21.0 ± 1.9
300	27°	0.95	18.6 ± 2.0
300	44°	1.50	9.4 ± 0.6

greatly from the free pion-nucleon ratios. Instead of the expected value of 9 near the P_{33} pion-nucleon resonance we find $R \approx 19$ at all energies between 180 MeV and 300 MeV at the momentum transfer $q = 0.95 \text{ fm}^{-1}$. (See table II). Apparently, even for the weakly-bound deuteron, the residual core (which is just a neutron in this case) is not simply a spectator. For the single data point measured at $q = 1.50 \text{ fm}^{-1}$ for ${}^2\text{H}(\pi^\pm, \pi^{\pm'} p)n$ at $T_\pi = 300 \text{ MeV}$, we find $R \approx 9$. These results on the smallest composite nucleus ${}^2\text{H}$ and the other few-body nuclei, ${}^3\text{He}$ and ${}^4\text{He}$, will be important in understanding the pion-nucleus interaction.

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Fig. 1. Time-of-flight (TOF) spectra for the reactions ${}^2\text{H} + \pi^+$ (top panel), and ${}^2\text{H} + \pi^-$ (bottom panel) are shown. The inelastic $p + n + \pi$ reaction branch for which the proton is detected, is seen at a TOF between 4 and 5 ns, whereas elastically scattered deuterons are at a TOF around 10 ns. The incident pion energy is 240 MeV. The data are binned in 0.5 ns segments.

Fig. 2. Pulse-height spectra of the CsI-phoswich detectors using the “short gate” (arbitrary unit) for the ordinate and the “long gate” (arbitrary unit) for the abscissa. The signals are from knocked-out particles in coincidence with “good” pion events in the LAS, in this case π^+ incident on ^2H . There are three regions of interest:

- (a) the region along the line with slope of 2.5; these events are charged particle that are stopped in the plastic. They are mostly recoiling deuterons from elastic scattering.
- (b) the region along the line with slope of 0.6; these events have left no or a vanishingly small amount of energy in the plastic, but deposit energy in the CsI crystal. These signals are mostly from neutrons and/or photons originating at the target and creating ionizing radiation by their interactions with the scintillator material.
- (c) the region between these lines contains events which deposited energy in both the plastic and the CsI. They are mostly protons from the knockout reaction.

2.4 Test run for LAMPF Exp. 1267, “Elastic scattering of π^+ and π^- from polarized ^3He at $T_\pi = 180$ to 475 MeV”

Spokespersons: D. Dehnhard (U. Minnesota), G. R. Burleson (New Mexico State U.), and O. Häusser (TRIUMF).

This experiment will measure analyzing powers A_y for both π^+ and π^- elastic scattering from polarized ^3He at incident energies between $T_\pi = 180$ MeV and 475 MeV. The polarized ^3He target developed by Häusser and collaborators at TRIUMF will be used (Fig. 1). The proposed measurements are in an energy region where the π -nucleon force is strongly energy- and isospin-dependent.

Theoretical calculations predict that these dependences result in strongly energy-dependent A_y which differ for π^+ and π^- . Excellent Faddeev wave functions are available for ^3He which imply that the spin of ^3He is nearly 90% due to that of the unpaired neutron. Thus nuclear structure uncertainties are minimized and information on the spin- and energy-dependence of the π -neutron interaction in nuclei and the π -nucleus reaction mechanism will be obtained.

In January of 1992 we presented this proposal to the LAMPF Program Advisory Committee. 840 hours of beam time were approved. The PAC suggested that a test run should be done on an unpolarized target prior to scheduling the experiment in order to determine the level of background events and to develop methods of background reduction should that be necessary. Large background is expected from reactions on the glass cell which contains the pressurized helium gas. The test was done in P³E between Oct. 8 and 12, at the end of the last run cycle in 1992. As proposed, the Large Acceptance Spectrometer (LAS) was used to detect the scattered pions. We had about 36 hours of beam on target with a primary proton beam current ranging from 60 to 600 μA . We did measurements with different beam conditions and with and without veto detectors in the beam halo. A detailed account of the test run is presented below.

The participants in the test run were: E. Brash, W. Cummings, B. Larson, and R. Henderson (TRIUMF), C. L. Morris and S. Penttillä (LAMPF), Mark Jones (Rutgers), Brent Park (NMSU), Michal Palarczyk, Michelle Espy, James Langenbrunner, and D. Dehnhard (UofM).

2.4.1 Target

The TRIUMF polarized ^3He target uses a cylindrical glass cell of about 46-mm inner diameter with approximately hemispherical end caps (Fig. 2). Including the end caps, the target has a length of about 60 mm. The thickness of the wall of the cylindrical part of the cell is about 1.5 mm and that of the end caps is about 0.4 mm.

The cell is operated at a pressure of between 7 and 10 atm. At 7 atm. (at room temperature) and assuming a usable length of 40 mm, the usable areal density of the ^3He in the target is 4 mg/cm². The glass is made of alumino-silicate (Corning 1720) and has a total mass of 13 g. The areal density of the glass in the end caps is about 130 mg/cm².

When the target is to be polarized by the laser beam, hot air is blown into the “oven” to warm up the cell in order to evaporate a small amount of Rubidium in the cell. The Rb is polarized by optical pumping using two 20-Watt Class IV Argon lasers and two 4-Watt Ti-Sapphire infrared lasers. The atomic polarization of the Rb is then transferred to the ^3He nucleus by the Fermi contact hyperfine interaction. A small amount of nitrogen gas (100 Torr) in the cell serves as a buffer gas. The number density of nitrogen nuclei is less than 4% of that of ^3He .

The pion beam enters the cell along the cylinder’s symmetry axis, and the polarizing laser beam enters the cell from below at a right angle to the scattering plane (see Fig. 1). For the test runs we used only the glass cell held within the target oven. The oven, indicated in Fig. 1 by the rectangular frame, is made of Vespel and has thin Kapton windows.

2.4.2 Pion Beam

All measurements were done at the incident energy of $T_\pi = 220$ MeV which is one of the proposed energies. At 220 MeV the pion flux in the P^3 channel reaches about 60% of its maximum which is at 300 MeV. We used the π^+ beam for its higher intensity and because it is not quite as clean as the π^- beam. Surely, if we succeeded in obtaining clean spectra with π^+ we would get them also with π^- .

In order to assure a high pion flux and a small beam spot on the target, we used an achromatic beam tune. With the particular beam tune chosen by us, the beam livergence

at the target was about 44 mrad horizontally and 22 mrad vertically. Thus, the cross section of the beam does not change much along the 60-mm length of the target. As apparent from pictures of the beam cross section taken by placing photographic film into the beam, most of the beam was focussed to a spot within an area of less than 15-mm width and 20-mm height when the beam collimator right after the A2 production target was in position. With the A2 collimator out, the beam spot was about 20 mm wide and 30 mm high.

The center parts of the hemispherical end caps (Fig. 2) of the target cell are exposed to the full beam and the remainder of the cell lies within the halo of the beam which contains a couple of percent of the beam intensity. Information on the position of the interaction vertex at the target can be obtained from the LAS wire chambers in a projection on the YTGT vs. XTGT plane (YTXT). Here YTGT measures the location of the scattering event on the target projected on an axis in the reaction plane perpendicular to the central ray entering the LAS spectrometer and XTGT is the coordinate perpendicular to the reaction plane (Fig. 2).

Since all proposed measurements will be done near a scattering angle of 90° , the information on YTGT can be used to eliminate the events from the end caps by a YTGT cut. Note that at $\theta_{LAS} = 90^\circ$, $YTGT = -Z$, where $+Z$ is the direction of the incident beam. (When drawing Fig. 2, $\theta_{LAS} = 80^\circ$ was chosen in order to distinguish between the YTGT and Z coordinates).

A plot of events in the YTGT vs. XTGT plane shows clearly the high rates from the end caps of the cell (Fig. 3). These events are easily eliminated by a YTGT cut. Also seen are events from the top and the bottom of the cell which can be eliminated by a cut on XTGT.

Events from the left and right sides of the cylindrical walls are indistinguishable from events from the cell's interior because the LAS wire chambers do not allow tracking of events in the direction perpendicular to the YTGT/XTGT plane. Thus, events from interactions with the side walls of the cell have to be eliminated or at least reduced significantly by collimation (passive and/or active).

2.4.3 Veto Detectors

We constructed a number of plastic scintillator detectors for use as active collimators. We also built a lead collimator for use 2-m upstream from the target to reduce the beam halo and for some of the runs we used existing tungsten bricks for horizontal collimation near the target cell.

Two of the scintillators were half rings of 30-mm inner diameter and 50-mm outer diameter viewed by individual phototubes. These scintillators intercepted particles heading towards the cylindrical wall of the target cell. Two additional scintillators were of rectangular shape with half circles of 50-mm diameter cut out to avoid double counting events that would be coincident with the half ring scintillators. These rectangular detectors intercepted particles heading towards the cell holder and target oven frame.

Prior to the test run we found that the photomultiplier tubes can operate without significant pileup of signals up to an instantaneous rate of about $5 \times 10^6 \pi/\text{sec}$ which, at a duty factor of 5.5%, corresponds to an average rate of about $3 \times 10^5 \pi/\text{sec}$. If 2% of the beam is intercepted by one of the veto scintillators, that would correspond to an average beam rate of $1.5 \times 10^7 \pi/\text{sec}$. Thus, unless passive collimation can reduce the beam halo significantly, the beam had to be limited to less than about $1.5 \times 10^7 \pi/\text{sec}$ if the vetoes were to be used.

In order to find the maximum possible beam flux at which good data could be taken even without the veto scintillators, we also did several runs with the veto detectors turned off. The results from this part of the test will be presented next.

2.4.4 Test Runs

A. Tests Without Veto Detectors

We did most measurements with the momentum acceptance of the P^3 channel set at $\Delta p/p = 1\%$. When the A2-target collimator is out, this setting gives a beam on target of about $10^8 \pi/\text{sec}$. (The A2-target collimator is located close to the A2-target at the entrance of the P^3 channel). When the A2-target collimator is in, the beam current is reduced by about a factor of 3.5 and its size is reduced such that interactions with the cylindrical cell walls become much less frequent. In order to reduce interactions with the side walls of the

cell for the case with the A2-collimator out, we installed tungsten bricks near the target as a shielding. Two bricks (of 8.5 in. length, 4 in. height, and 1.2 in. width) were placed in front of the target such that the long side of the brick pointed towards the cell walls and was slightly off parallel the beam axis to accommodate the calculated beam divergence.

We found that passive collimation 2m upstream of the target was not sufficient but that collimation near the target was more effective than we had assumed after many discussions prior to the experiment. Problems usually arise with collimation near the target when measurements are made at small scattering angles where the large cross sections for forward-angle scattering create a large background. Our test measurements were done at 90° and the real experiment is to be done near 90° where scattering by a collimator near the target is less important. We found that the events that come from the side walls of the cell were reduced by collimation with the tungsten bricks.

We now present, in order of increasing number of cuts on several LAS variables, the missing mass (MM) spectra from a cell filled with ^3He . These spectra were taken with the A2-target collimator out and using the tungsten bricks near the target. Fig. 4 is the MM spectrum of all good LAS events, that is, the “good chambers” tests and the complete particle-identification (PID) box were applied. In addition, a few relatively loose cuts were placed on variables that, for example, reduce the number of muons from pion decay. Trace back of the trajectories of muons is likely to result in an incorrect position on the YTXT plane and could thus add to background within the cell. This spectrum is dominated by events from the end caps.

Next we eliminate the events from the end caps by a cut on YTGT. The number of total counts in the MM spectrum (Fig. 5) is now much reduced and there is a hint of a peak near $\text{MM} = 0$, where the elastic scattering events from ^3He are expected. Clearly, the background is still too large to extract a meaningful yield from this hint of a peak. However, once a cut is placed on XTGT as well (by using a “box” on YTXT), we obtain a clear peak near missing mass 0. (See Fig. 6, solid line histogram). The size of the box on an associated YTXT spectrum is shown in Fig. 3.

We have also taken spectra from an empty cell. The empty cell is close to the full cell in

size, shape, and wall thickness, but the full and empty cells are not identical due to limitations inherent to glass-blowing artistry. The bar histogram in Fig. 6 is the empty target spectrum, normalized to integrated beam current for comparison to the full-target spectrum (solid line histogram). The yield in the region of $MM = 0$ is clearly much smaller in the empty-cell than in the full-cell spectrum.

The spectra just shown were taken with the channel tune and collimation set to the high beam flux of $10^8 \pi/\text{sec}$ at a primary beam current of $600 \mu\text{A}$. During some of the runs the primary proton beam was actually smaller than $600 \mu\text{A}$, due to the radiation safety requirements imposed on LAMPF operation. However, this affected only the running time, not the spatial distribution of the pion beam on target that determines the peak to background ratio.

Still cleaner spectra (Fig. 7), even without the tungsten collimation, were obtained when the A2-target collimator was in. This causes a smaller beam spot and therefore less background, however, at the expense of about a factor of 3.5 in beam flux. (It should be noted that the spectrum in Fig. 7 was taken with a magnetic field different from that used for the other spectra. This field placed events above $MM = 15 \text{ MeV}$ outside the acceptance of the LAS).

The reasonable signal-to-background ratio in Fig. 6 (A2-target collimator out) implies that good asymmetry data can be taken in this mode (no vetoes). We expect, however, that we can improve the signal-to-background ratio with passive collimation and veto detectors as clean-up slits.

B. Tests With Vetoes

We did the veto tests at the beginning of the run without the tungsten brick collimation. In order to prevent overloading the phototubes we ran with reduced beam current of about $10^7 \pi/\text{sec}$.

The scintillators were designed to provide a software veto for events from scattering of pions by the cylindrical walls of the gas cell. For this purpose time-of-flight spectra were taken for each veto detector using the LAS trigger as a start and a signal from the veto detectors as a stop. A typical spectrum is shown in Fig. 8 for one of the half-circular

detectors. The sharp peak near channel 370 is primarily from true coincidences, i. e., from pions which passed the scintillator and, after scattering in the target, generated an LAS trigger. The other peaks are from random coincidences between a pion creating an LAS trigger and another particle passing through the scintillator. These events are from particles from other beam micropulses and are not to be vetoed. The spacings between the peaks are 5 ns as expected from the microstructure of the beam.

Only the events in the narrow peak (primarily true coincidences) were rejected by the software. Note that this peak is only about 1 ns wide and that it contains some random coincidences. Their rejection leads to a loss of potentially good events. We estimate that there are about 30 random coincidences in that peak out of a total of 1800 random coincidences. Thus the fraction of potentially good events rejected by one veto was only about 2% (or about 4% for the two small veto detectors) for the beam conditions of this run.

The effect on the YTXT spectrum of using the veto is demonstrated in Fig. 9. In this figure, events in the YTXT plane are shown both with veto (upper spectrum) and without veto (lower spectrum). Clearly, the number of events from the top and bottom of the cell walls is considerably smaller in the upper spectrum than in the lower one.

For the real experiment we will prepare passive collimation close to the target not only horizontally but also vertically and use the vetoes only as an active clean-up collimator. We do not expect to be limited by the veto rates because the good results with the use of the tungsten bricks (and without veto) have shown that the beam halo can be reduced by simple collimation.

2.4.5 Conclusion

We have shown during the course of the test run that LAMPF experiment No.1267 can be done. Moreover, we have shown that there are several ways in which this experiment may be run successfully. With no vetoes, tungsten brick collimation, and the A2-target collimator out (allowing a pion current of about $10^8 \pi/\text{sec}$) we obtained spectra of the quality of Figure 6. Still cleaner spectra (Fig. 7) were achieved with the A2-target collimator in, thus running at a reduced pion current. We also found that at an average veto rate of $2 \times 10^5/\text{sec}$, the veto

detectors efficiently reduce the number of background events.

Due to a lack of beam time we were not able to combine the tests of active and passive collimation. However, we are convinced that during the actual experiment a combination of tight passive collimation near the target (with an aperture adjusted to the calculated beam divergence) followed by veto detectors merely as active clean-up slits, will allow us to run at a beam rate of $10^8 \pi/\text{sec}$ with a peak/background ratio approaching that shown in Fig. 7 without a sacrifice in beam current. Thus it appears clear that Exp. 1267 can be done well with LAS at P³.

Fig. 1. Layout of the polarized target.

Fig. 2. Sketch of target cell and coordinate system. (See text).

Fig. 3. Position spectrum of scattered pions, projected on YTXT plane.

Fig. 4. Missing Mass spectrum from full cell using the complete particle identification (PID). The A2-collimator is out.

Fig. 5. Missing Mass spectrum as for Fig. 4 but with cut on YTGT excluding events from the end caps.

Fig. 6. Missing Mass spectrum as for Fig. 4 but with box on YTXT (solid line histogram) and Missing Mass spectrum from empty cell (bar histogram).

Fig. 7. Missing Mass spectrum from full cell, with box on YTXT, but now with A-2 target collimator in. An LAS field is used which is slightly lower than for the other spectra and places events above about $MM = 15$ MeV outside the LAS acceptance.

Fig. 8. Time-of-flight spectrum from one of the half-circular veto detectors. The peak near channel 370 contains the true coincidences between the LAS trigger as start and a veto detector signal as stop. Only the events in this narrow peak are being vetoed.

Fig. 9. YTXT position spectra from measurements with vetoes. A2-target collimator is in. Top: Events that passed the veto detectors are excluded; bottom: Events that passed the veto detectors are included.

2.5 Differential cross sections $d\sigma/d\Omega$ for π^+ scattering from ${}^6\text{Li}$ and ${}^{13}\text{C}$

2.5.1 Measurement of $d\sigma/d\Omega$ for ${}^6\text{Li}(\pi^+, \pi^+)$ at $T_\pi = 100, 134, 164, 190$ and 219 MeV (LAMPF Exp. 1220)

Spokesmen : B. Brinkmüller and E. Boschitz (U Karlsruhe), Participants: B. Brinkmüller, S. Ritt, R. Meier (U Karlsruhe), S. J. Greene (LAMPF), C. M. Edwards and M. Palarczyk (UofM).

${}^6\text{Li}$ shows typical properties of heavier nuclei but is sufficiently light to allow calculations of nuclear processes using shell-model as well as cluster-model wave functions. Currently there exists considerable theoretical interest in tests of these wave functions. Among the many studies of the six-nucleon system only relatively few have been undertaken with pions. Pion elastic and inelastic scattering from ${}^6\text{Li}$ were investigated at a few energies, but in some cases over only a limited angular range.

Recently at PSI, the vector analyzing power iT_{11} was measured for $\pi^+ - {}^6\text{Li}$ elastic and inelastic scattering (3^+ , $T=0$ state 2.19 MeV) at the incident energies of 100, 134, 164, and 219 MeV, in the angular range between 40° and 125° using a vector polarized ${}^6\text{LiD}$ target [Rit92]. Large spin-dependent effects were observed. The data have been compared with several theoretical predictions. None of the calculation was able to reproduce the entire data set.

In the course of the theoretical analysis of the iT_{11} data, it became clear that the existing differential cross section data are too limited in energy and angular range. An additional difficulty was that differential cross sections measured recently at PSI, show some inconsistencies with previously published data. Thus it is clear that there is a need for high-quality cross section data to complement the polarization data.

During the fall of 1992 we have therefore measured differential cross sections using the EPICS spectrometer. We took data at all energies (except one) for which polarization data exist, i. e., at $T_\pi = 100, 134, 164, 190$ and 219 MeV. Data at 190 MeV data will be taken in the near future at PSI. The angular range spanned from 30° to 120° . The spectra were taken

posed to measure the angular distribution for π elastic scattering on ^{13}C in an angular range from 25° to 120° , using the high-resolution EPICS spectrometer. The measurements were done during the last run cycle of 1992 at $T_\pi = 130$ and 223 MeV, the energies of Exp. 1025U. The allotted beam time was sufficient to take data only with π^+ . Spectra were taken in 5° steps. The accumulated statistics were sufficient to use 1° -binning in replay.

The preliminary elastic scattering cross sections at $T_\pi = 130$ MeV display well defined first and second minima, the second being deeper than in the previous experiment. The difference in the depth of the second minimum can be explained by the worsened angular resolution caused by the bending of the particle trajectories by the polarizing magnet. EPICS without the polarizing magnet has much better angular resolution. In addition, its energy resolution is significantly better than that of LAS.

The $T_\pi = 223$ MeV angular distribution is in reasonable agreement with the old data at small and medium angles but (as for the data at 130 MeV) the error bars of the new data are much smaller which is very important to put constraints on theoretical models. In the region of second minimum, the distributions differ considerable. The old cross sections in this region are systematically larger (roughly by factor of 10) than the current results. Thus at $T_\pi = 223$ MeV at about 90° and above, the 1025U slab target data suffer from a serious normalization problem. We note that the EPICS data show evidence for a third minimum at about 110° after a relatively sharp second minimum near 90° .

As for the case of ^6Li which was discussed in the previous subsection, the new data for ^{13}C should allow a more comprehensive analysis of the asymmetry data.

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solid line in (Fig. 1) is the predicted $|F_{M1}|^2$ using Cohen and Kurath (CK) wave functions[8, 9] in the code ALLWORLD.[10] The squares of the isoscalar (isospin transfer $T=0$) and isovector ($T=1$) form factor amplitudes are shown as dotted and dashed lines, respectively. The $T=1$ part is dominant at large momentum transfers, $q \geq 1.5 \text{ fm}^{-1}$. At $q \approx 0.6 \text{ fm}^{-1}$, the $T=0$ and $T=1$ parts are of comparable magnitude. The square of the $T=1$ spin part (without the convection current terms) (chain-dotted) is a factor of $[(\mu_p - \mu_n)/(\mu_p + \mu_n)]^2 = 28.5$ larger than that of the $T=0$ spin part (chain-dashed). Here μ_p (μ_n) is the proton (neutron) magnetic moment. The coherent addition of the spin and current terms results in the above-mentioned different q -dependences of the $T=0$ and $T=1$ parts of $|F_{M1}|^2$ and gives a good fit to the experimental $|F_{M1}|^2$ up to $q \approx 1.3 \text{ fm}^{-1}$.

The asymmetry in pion scattering has an isospin sensitivity very different from that of $|F_{M1}|^2$. For P_{33} pion-nucleon resonance dominance, the ratio r of the $T=0$ and $T=1$ pion-nucleus scattering amplitudes is, independent of q , $r=+2$ for π^- and $r=-2$ for π^+ if protons and neutrons contribute equally to the transition and if first-order processes dominate. Terms analogous to the current terms in electron scattering are thought to be small in pion scattering.

Because of this very different isospin dependence of the spin transitions by electron and pion elastic scattering, the pion asymmetry provides information complementary to the magnetic form factor for comparison with nuclear model predictions, especially for the isoscalar spin part of the transition density. We note that pion-induced single-charge-exchange (SCX) reactions[3] proceed exclusively by the isovector parts of F and G .

The nuclear transition density amplitudes are usually classified[9] according to the total and the orbital angular momentum transfers J and L , and the spin transfer S . Specifically for elastic scattering on a spin $J_0 = \frac{1}{2}$ nucleus such as ^{13}C , there are three possible combinations (Table I) of $J(LS)$: $0(00)$, $1(01)$, and $1(21)$ since the $L=1$ terms can be neglected in a first-order calculation. In terms of the nuclear structure amplitudes, the pion-nucleus amplitude F is proportional to the $0(00)$ part and G is proportional to a combination of the $1(01)$ and $1(21)$ parts.

The elastic scattering cross sections and asymmetries were calculated by combining the

We note that the CK and TW values are very similar for 1(01) but totally different for 1(21) (Table I). What is primarily a 1(21) neutron particle-hole (p-h) amplitude in CK, is almost a pure proton (p-h) amplitude in TW. We have therefore studied how A_y is affected by renormalizing the 1(21), that is, the “quadrupole spin-flip” amplitude, by a factor α . The solid line in Fig. 3 shows again the calculated A_y with the 1(21) value of CK. Arbitrarily changing the sign of the 1(21) amplitude essentially flips the sign of the asymmetry (dashed line). Using two times the CK value nearly doubles A_y (chain-dashed line) and making the 1(21) piece zero gives a very small A_y (dotted line) which arises only from the interference of the 0(00) and 1(01) amplitudes. Thus A_y is exceedingly sensitive to the quadrupole spin-flip term. However, it appears that no value of the 1(21) amplitude would fit the data with the 0(00) and 1(01) parts left unchanged.

In order to explore the effects on A_y of possible higher-shell components in the nuclear wave functions, we have also done calculations with the phenomenological wave functions of Ref. [14] which are a mixture of 1p and 2p shell components. We find (Fig. 4) that for both π^- and π^+ the 2p admixtures reduce the asymmetry near the first diffraction minimum but increase it near the second one with no improvement in the fit to the data. Relatively larger effects from the 2p admixtures were found in DWIA calculations for SCX.[15]

Before conclusions can be drawn from the asymmetries about the validity of nuclear wave functions, the pion-nucleus reaction model needs to be understood better. Preliminary calculations in the Δ -hole model[4] show significant differences in the asymmetries when compared to first-order optical potential predictions. Pion scattering on polarized ^3He might provide[16, 17, 18] the needed information for a thorough test of reaction models because the nuclear structure of ^3He is very well known and excellent wave functions exist from 3-body Faddeev calculations.[19] A first experiment on polarized ^3He has recently been performed at TRIUMF at $T_\pi = 100$ MeV [20]. These measurements should be extended to higher energies in order to exploit the strong energy dependence of the π -nucleon interaction and the larger range of q that becomes accessible.[18]

In conclusion, recently measured asymmetry data for pion scattering from ^{13}C are only poorly understood theoretically. If the pion-nucleus reaction dynamics were reliably known,

these data would provide information on the spin transition density, specifically its isoscalar component, which is needed for tests of nuclear structure models. The best test of the reaction models may be provided by measurements of pion scattering on polarized ^3He since its structure is well known.

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Fig. 1. Magnetic form factor squared, $|F_{M1}|^2$, from $^{13}\text{C}(e,e)$. Data of Ref.[7]. Solid line: prediction with program ALLWORLD[10] using CK densities. Dashed (dotted) line: T=1 (T=0) parts; chain-dashed: T=0 spin part only; chain-dotted: T=1 spin part only.

Fig. 2. Elastic differential cross sections and asymmetries for $^{13}\text{C}(\pi, \pi)$ at 130 MeV. Data of Ref.[2]. Solid (dashed) line: DWIA calculation with CK (TW) densities.

Fig. 3. Elastic differential cross sections and asymmetries for $^{13}\text{C}(\pi, \pi)$ at 130 MeV. Data of Ref.[2]. Solid line: DWIA calculation with CK densities ($\alpha=1$). Other curves, see text.

Fig. 4. Data as for Fig. 3. Solid line: DWIA calculation with TW densities. Dashed (chain-dashed) line: with 16% (6%) 2p-shell admixture.

3.2 Preprints and title pages of published papers

A brief summary of the completed work was given on page 1 of this report. Here we attach preprints of a few selected published papers and the front pages of other papers that were published in refereed journals.

4 Lists of publications etc.

4.1 Papers published in refereed journals

1. " $^4\text{He}(\pi, \pi'p)^3\text{H}$ reaction: Quasi-Free and Resonance Scattering,"
M. K. Jones, D. Dehnhard, S. K. Nanda, S. Sterbenz, C. L. Morris, M. Plum, J. D. Zumbro, Ahmed Hussein, D. S. Oakley, M. J. Smithson, A. L. Williams, J. McDonald, M. A. Bryan, A. H. Fuentes, M. Lynker, D. Crockett, M. A. Machuca, S. Mordechai and C. Fred Moore, Phys. Rev. C **42**, R807 (1990)
2. " $^{208}\text{Pb}(\pi^\pm, \pi^\pm'n)$ Reaction Near the Giant Resonance region,"
Sung Hoon Yoo, A. Williams, S. Mordechai, C. Fred Moore, C. L. Morris, S. J. Seestrom-Morris, M. Jones, S. Sterbenz, D. Dehnhard, D. S. Oakley and A. Fazely, J. Phys. G: Nucl. Part. Phys. **16**, L89 (1990).
3. "Analyzing Powers for the Reaction $\pi^- \bar{p} \rightarrow \pi^0 n$ at $T_{\pi^-} = 161$ MeV,"
J. J. G3rgen, 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. Brinkm3ller. D. Dehnhard, Yi-Fen Yen, S. H3ibråten, H. Breuer, B. S. Flanders, M. A. Khandaker, D. L. Naples, D. Zhang, M. L. Barlett, G. W. Hoffmann and M. Purcell, Phys. Rev. D **42**, 2374 (1990).
4. "Asymmetry measurements of pion elastic scattering from polarized ^{13}C in the energy region of the P_{33} resonance,"
Yi-Fen Yen, B. Brinkm3ller, D. Dehnhard, S. M. Sterbenz, Yi-Ju Yu, Brian Berman, G. R. Burleson, K. Cranston, A. Klein, G. S. Kyle, R. Alarcon, T. Averett, J. R. Comfort, J. J. G3rgen, B. G. Ritchie, J. R. Tinsley, M. Barlett, G. W. Hoffmann, K. Johnson, C. F. Moore, 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, H. T. Fortune, E. Insko, R. Ivie, J. M. O'Donnell, D. Smith, M. A. Khandaker and S. Chakravarti, Phys. Rev. Lett. **66**, 1959 (1991).

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6. "Elastic scattering of π^+ and π^- from ^4He between 90 and 240 MeV,"
B. Brinkm6ller, C. L. Blilie, D. Dehnhard, M. K. Jones, G. M. Martinez, S. K. Nanda S. M. Sterbenz, Yi-Fen Yen, L. G. Atencio, J. A. Faucett, S. J. Greene, C. L. Morris, S. J. Seestrom, G. R. Burleson, K. S. Dhuga, R. W. Garnett, K. Maeda, C. Fred Moore, S. Mordechai, A. Williams, S. H. Yoo, and L. C. Bland, *Phys. Rev. C* **44**, 2031 (1991).
7. "Angular distribution coefficients for (γ, X) reactions with linearly polarized photons,"
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S. M. Sterbenz, D. Dehnhard, M. K. Jones, S. K. Nanda, C. E. Parman and Yi-Fen Yen, K. W. Jones, C. L. Morris, *Phys. Rev. C* **45**, 2578 (1992).
9. "CsI-phoswich detector for charged-particle identification,"
J. L. Langenbrunner, C. L. Morris, R. M. Whitton, *Nucl. Instr. and Meth.* **A316**, 450 (1992) (Letter to the Editor).
10. "Test of superconducting radio-frequency cavity bombarded by protons,"
J. M. O'Donnell, B. J. Mc Cloud, C. L. Morris, J. B. McClelland, B. Rusnak, H. A. Thiessen, J. L. Langenbrunner, *Nucl. Instr. and Meth. A* **A314**, 409 (1992).
11. " $^4\text{He}(\pi, \pi' p)^3\text{H}$ reaction near the P_{33} π -nucleon resonance,"
M. K. Jones, D. Dehnhard, S. K. Nanda, S. M. Sterbenz, C. L. Morris and M. Plum, J. D. Zumbro, Ahmed H. Hussein, D. S. Oakley, M. J. Smithson, A. L. Williams,

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12. "Evidence for direct triton knockout in the $^4\text{He}(\pi, \pi t)$ reaction," J. L. Langenbrunner, M. K. Jones, D. Dehnhard, C. L. Morris, W. R. Gibbs, *Phys. Rev. Lett.* **69**, 1508 (1992).
 13. "Pion production at small angles for PILAC," J. L. Langenbrunner, C. P. Pillai, *Nucl. Instr. and Meth. A* (in press) (1992) and Los Alamos Report No. LA-UR-91-1268.

4.2 Invited talks

1. "Systematic Study of Pion Elastic scattering from ^4He in the Region of the $P_{3,3}$ Resonance," B. Brinkmüller and D. Dehnhard, EPS Nuclear Physics Study Conference, held at Crete, Greece, May 20-26, 1990.
2. "Pion Scattering Experiments with Polarized Nuclear Targets," B. Brinkmüller and D. Dehnhard, EPS Nuclear Physics Study Conference, held at Crete, Greece, May 20-26, 1990.
3. "High Energy Kaon and Pion Scattering," B. Brinkmüller, D. Dehnhard, and S. Chakravarti, Workshop on Science at the KAON Factory, held at TRIUMF, Vancouver, B. C., Canada, July 23-28, 1990.
4. "High Energy Pion Scattering with PILAC." D. Dehnhard, Workshop on Physics with PILAC, Los Alamos, N.M., August, 1990.
5. "Pion-nucleus interactions at P_3 energies," D. Dehnhard, Meeting on Physics with Polarized Targets, August 18, 1991, LAMPF, Los Alamos, N.M.
6. "Pion elastic scattering on a polarized ^{13}C target", D. Dehnhard, Yi-Fen Yen, M. A. Franey, and S. Chakravarti, International Symposium on Mesons and Light Nuclei V, September 1-6, 1991, Prague, C.S.F.R.

7. "Spin excitations of nuclei by pions", S. Chakravarti, C. M. Edwards, D. Dehnhard, and M. A. Franey, International Symposium on Mesons and Light Nuclei V, September 1-6, 1991, Prague, C.S.F.R.
8. "Pion scattering and reactions on polarized nuclei," D. Dehnhard, Indian Summer School on Nuclear Physics, September 8-13, 1991, Sázava, C.S.F.R.
9. "Results of BGO resolution studies," J. Langenbrunner, Informal Meeting of Neutral Meson Spectrometer (NMS) Collaboration, November 15, 1991, LAMPF, Los Alamos.
10. "Effect of proton beam on Scruncher performance", J. Langenbrunner, Workshop on PILAC Superconducting Cavity, October 5, 1991, LAMPF, Los Alamos.
11. "Evidence for direct triton knockout in the ${}^4\text{He}(\pi, \pi t)$ reaction," J. Langenbrunner, April 31, Duke University, 1992.
12. "From the perspective of a teacher," J. Langenbrunner, Los Alamos Science Student Program, a DOE-sponsored science program for High School Students in New Mexico, September 26, 1992.

4.3 Contributed papers and abstracts

1. "Pion Elastic Scattering from Polarized ${}^{13}\text{C}$ in the Energy Region of the [3,3] Resonance." Yi-Fen Yen, B. Brinkmøller, D. Dehnhard, S. M. Sterbenz, Yi-Ju Yu, Brian Berman, G. R. Burleson, K. Cranston, A. Klein, G. S. Kyle, R. Alarcon, T. Averett, J. R. Comfort, J. J. Görden, B. G. Ritchie, J. R. 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, H. T. Fortune, E. Insko, R. Ivie, J. M. O'Donnell, D. Smith, S. Høibråten, M. A. Khandaker and S. Chakravarti, Proceedings 7th International Conference on Polarization. Phenomena in Nuclear Physics, Paris, July 9-13, 1990, ed. by A. Boudard and Y. Tien, Colloque de Physique **51**, suppl. no. 22, p. C6-587 (1990).

2. "Asymmetry Measurements for the (π^+ , π^0) Reaction on a polarized ^{13}C Target,"
J. J. G3rgen, 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. N. Knudson, S. Penttilä, N. Tanaka, B. Brinkm3ller, D. Dehnhard, Y.F. Yen, B. S. Flanders, D. Zhang, M. Barlett, G. W. Hoffman, M. Purcell and S. H3ibråten, Paper contributed to the 7th International Conference on Polarization Phenomena in Nuclear Physics, Paris, July 9-13, 1990, ed. by A. Boudard and Y. Trien, Colloque de Physique **51**, suppl. no. 22, p. C6-583 (1990).
3. "Polarization Asymmetries for the reaction $\pi^- \bar{p} \rightarrow \pi^0 n$ at $T_{\pi^-} = 161$ MeV,"
J. J. G3rgen, 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. N. Knudson, S. I. Penttilä, N. Tanaka, B. Brinkm3ller, D. Dehnhard, Yi-Fen Yen, B. S. Flanders, D. Zhang, G. W. Hoffman, M. Purcell, S. H3ibråten. Paper contributed to the 7th International Conference on Polarization Phenomena in Nuclear Physics, Paris, July 9-13, 1990.
4. "Asymmetry Measurements of Pion Elastic Scattering from Polarized ^{13}C ,"
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