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C. Fred Moore
Department of Physics
University of Texas at Austin
Austin, Texas 78712-1081

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1 Introduction

This report summarizes the work carried out by personnel from the University of Texas at Austin at the Los Alamos Clinton P. Anderson Meson Physics Facility (LAMPF) during the three calendar years 1988-1990 under grant DE-FG05-87ER40343 between the University of Texas at Austin and the United States Department of Energy.

One of our faculty has been on site (at LAMPF) during five months or more of each year. A research faculty member has been on site for the year. An average of five graduate students have been associated with this program, most being in residence at LAMPF.

The research activities involved experiments done with the Energetic Pion Channel and Spectrometer (EPICS), the Low Energy Pion Channel (LEP), the Pion and Particle Physics Channel (P^3), and the High Resolution Spectrometer (HRS).

A brief overview of work supported by this grant is given in section 2. This report contains a list of published papers and preprints in section 7, a list of abstracts of papers reported at scientific meetings in section 8, a list of invited papers in section 9. These papers summarize experiments undertaken in this grant period and indicate the work accomplished by the participants in this program of medium energy nuclear physics research. Much of the experimental work that has been attempted during the period covered by this report has either been published or submitted for publication. Section 4 contains a list of the recent proposals which we submitted to the Program Advisory Committee (PAC) at LAMPF or which we plan to initiate at the coming PAC meeting. Section 10 contains a list of personnel who have participated in this research program.

The research cited in this report is, in many cases, the collaborative effort of many groups associated with research at LAMPF. Collaboration with the Los Alamos National Laboratory, the University of Minnesota, the University of Colorado, the Louisiana State University, the Ben Gurion University of the Negev, the King Fahd University of Petroleum and Minerals, the Lawrence Livermore Laboratory, the New Mexico State University, Argonne National Laboratory, and the University of Pennsylvania is acknowledged.

Two Ph.D. degrees were granted by the University of Texas at Austin during this grant period based on experimental research done at LAMPF, bringing the total number of Ph.D.'s granted to Texas students supported by this grant in meson-nuclear physics to eleven.

2 Overview

Our program concentrates on pion physics experiments. Most of the experimental program was carried out using the Energetic Pion Channel and Spectrometer (EPICS), Pion and Particle Physics channel (P^3), and the Low Energy Pion physics channel (LEP). These facilities are unique in the world in their intensity, background rejection, and energy resolution. Several coincidence experiments are in progress and several are proposed in addition to the single arm experiments done with these facilities. The results obtained in the first two research years of this program have been published (or submitted) in several scientific reports and invited talks at international conferences.

2.1 Pion scattering from a polarized target

Inelastic pion scattering experiment #1025, which was approved with A⁺ priority, dealt with measurements of pion scattering from a polarized ^{13}C target. The main objective was to measure the asymmetry parameter A_y for $\pi^\pm$ elastic and inelastic scattering, over an angular range of 30° to 100° , from a polarized ^{13}C target at EPICS. The elastic-scattering results should be sensitive to spin-dependent effects in the pion-nucleus interaction, such as the Δ -nucleus spin-orbit interaction. The inelastic-scattering results are sensitive to the relative admixture of spin-flip and non-spin-flip contributions to the transitions. Polarized target experiments give new information about the pion-nucleus interaction that is not available from experiments with unpolarized targets, because the former measure the interference between amplitudes and the latter measure squares of amplitudes. The target system was assembled principally from polarized-target elements available at LAMPF; additional work was necessary for installation at EPICS. The experiment ran successfully during running cycles 57 and 58. Further details on this experiment are given in Section 4.3. Data analysis and reduction are now in progress.

2.2 Pion elastic, inelastic scattering, and pion absorption

In experiment #995 we measured angular distributions for π^+ and π^- scattering to low-lying collective states in ^{208}Pb at $T_\pi = 120$ and 250 MeV. These data will be used to identify π -nucleus reaction mechanism effects that could explain the energy-dependent values of M_n/M_p extracted for the Giant Quadrupole Resonance (GQR) in ^{208}Pb . In particular, we emphasized obtaining high-quality data for the 2_1^+ and 3_1^- states over a large angular range. Because the proton matrix elements extracted for the GQR vary with pion energy and are much smaller than expected, the comparison of proton matrix elements for these states with the electromagnetic values is extremely important.

In experiment #1016 we measured inelastic $\pi^\pm$ scattering on ^{27}Al and $^{28,29}\text{Si}$. It was desired to measure M_n and M_p for E2 and E4 transitions. This experiment will improve our understanding of how the addition of a valence particle or hole to the doubly closed $d_{5/2}$ subshell of ^{28}Si polarizes the core.

In experiment #1104, cross-sections to the GQR for the nuclei ^{90}Zr and ^{208}Pb have been measured with π^+ and π^- at energies from 350 to 550 MeV, i.e., above the $\Delta_{3/2,3/2}$ resonance region. The goal of this experiment is to give an accurate evaluation of neutron and proton transition amplitudes (M_n and M_p) extracted for GQR in those neutron excess nuclei. Those values of M_n and M_p obtained near the $\Delta_{3/2,3/2}$ resonance region are affected by uncertainties in the wave functions involved and the uncertain shapes of the neutron and proton transition densities at the nuclear surface, due to the short mean free path of the pion near the Δ resonance. The longer mean free path of the pion in the higher energy region may help to eliminate those uncertainties in extraction of the matrix elements.

Regarding experiment #1018, we have analyzed large-angle pion elastic data on ^{12}C and ^{16}O with standard first-order optical models using matter distributions deduced from electron scattering. We show that these models reproduce only the qualitative features of the data. However, much better agreement can be achieved with the same models provided the matter distributions are modified in a suitable way. At this stage it is not clear whether these corrections are applicable to all nuclei or whether they apply at energies other than those on resonance. To address these questions we propose to measure elastic excitation functions (at 175°) on ^6Li , ^{28}Si , and ^{58}Ni in the energy range from 100 to 250 MeV.

Experiment #992 sought to measure π^+ -scattering excitation functions for 1^+ states in ^{24}Mg and ^{28}Si . Measurements were made at beam energies of $T_\pi = 100, 130, 160, 190, 220, 250,$ and 280 MeV, with one angular distribution per nucleus at 160 MeV. Results were used to determine the effects of Fermi motion on the π -N effective interaction.

Experiment #1103 aims to measure the ratio of $(\pi^+, \pi^{+'})$ vs $(\pi^-, \pi^{-'})$ on various nuclei to provide information on proton and neutron transition densities at energies around the Roper resonance where the relative strength of pure proton and pure neutron transitions should be reversed as compared to the $\Delta_{3/2,3/2}(1232)$ resonance case.

For the pion absorption, experiment #1137 the LEP and P^3 channels at LAMPF will be used. In the low energy pion channel, we propose to measure the cross sections for π^+ and π^- absorption on ^{12}C , ^{58}Ni , and ^{208}Pb in which the final state includes two or more free protons. Data will be taken for π energies of 50, 100, 150, and 200 MeV. The energy and angular distributions of the outgoing protons are measured using a large solid-angle bismuth germanate BGO detector.

In the pion particle physics (P^3) channel, we measured the cross sections for π^+ and π^- absorption on ^{12}C , ^{58}Ni , and ^{208}Pb in which the final state includes two or more free protons. Data were taken for π energies of 200, 300, 400, and 500 MeV. The energy and angular distributions of the outgoing protons are measured using a large solid-angle BGO detector.

2.3 Pion DCX studies

Among the most exciting results obtained recently at LAMPF in pion physics is the observation of resolved giant-dipole resonances built on the isobaric analog states and the isovector giant dipole resonance built on another giant dipole. The isobaric analog and the giant dipole were both observed in a (π^+, π^0) single charge exchange reaction (with

a typical maximum cross section around $0.5 \rightarrow 1.0$ mb/sr). Therefore a combination of these resonances could, in principal, be reached in double charge exchange. However, until recently, none of these double resonances had been found.

The results obtained so far are exciting and have a potential for revealing new and interesting physics. Experiments #1050, #1118, and #1154 have demonstrated that pion DCX provides a unique reaction in which one can study the existence of double giant resonances in nuclei. The results indicate that the two new modes of nuclear excitations are observable in pion double charge exchange reactions. Due to the selectivity of the DCX reaction, which causes T_z to change by two units, these exotic states are observable even though they are located at high excitation energy where background from DCX to the continuum is large. The data show that the newly discovered resonances are general collective features of all nuclei for the double-dipole, and of all nuclei with $N - Z \geq 1$ for the GDR built on the IAS. In experiment #1118 at the Energetic Pion Channel and Spectrometer (EPICS), which ran for a full cycle in May-June 1989 at LAMPF, we observed a clear splitting of the giant dipole built on the isobaric analog state (GDR@IAS) in the $^{93}\text{Nb}(\pi^+, \pi^-)^{93}\text{Tc}$ reaction at $T_\pi = 292$ MeV. An important implication of the existence of double resonances was outlined recently by our collaboration and is discussed in detail in the preprint "Analog of the T_2 giant dipole resonance in light nuclei" attached to this report (Section 5.3). An overview on the relatively new phenomena of double resonance states can also be found in our preprint submitted to NATURE and attached to this report (Section 5.2).

Experiment #1028 ran in the fall of 1987 and produced the first known measurements of pion-induced double charge exchange in the energy range of $300 \rightarrow 550$ MeV on ^{14}C and ^{18}O . The experiment demonstrated that measurements of this type were feasible and also produced unexpected results as compared with currently accepted models for this reaction. In light of the success of #1028, experiment #1107 was performed in the fall of 1988 and yielded measurements of high energy DCX for ^{12}C , $^{40,42,44,48}\text{C}$, ^{24}Mg , ^{80}Se , ^{90}Zr , ^{197}Au , and ^{208}Pb . The results of these measurements will yield valuable constraints for current theoretical models for the DCX reaction mechanism. In order to provide a data base for the study of the isospin structure of the pion-nucleus interaction and to calibrate the optical potential at these high energies, experiment #1106 was performed in the summer of 1988. Elastic scattering with π^+ and π^- on ^{12}C , ^{40}Ca , ^{90}Zr , and ^{208}Pb was measured at 300, 400, and 500 MeV.

2.4 Coincidence measurements

For investigation of the multiparticle final state in pion interactions, we proposed the study of decay protons in the reaction $(\pi, \pi' p)$ as a test of charge symmetry. Comparisons of photo-proton and photo-neutron breakup of ^4He have provided evidence for a large violation of charge symmetry, presumably caused by forces other than the Coulomb force. However, pion inelastic scattering data show that the deviation from charge symmetry can be explained by the Coulomb potential only. In an attempt to resolve this argument on the existence of charge symmetry breaking forces other than Coulomb interactions, a series of

$(\pi, \pi' p)$ coincidence experiments on ${}^4\text{He}$ (# 998), ${}^{12}\text{C}$ and ${}^{208}\text{Pb}$ (# 1039) was conducted during the 1986-87 time span. The conclusion of these experiments is that there is no other force than Coulomb that breaks up charge symmetry, and the discrepancy between the result using electromagnetic probes and that using pions can be explained by direct-knock-out and semi-direct components, using the widely known Direct-Semidirect Model or Doorway-state Model.

3 Proposals

Proposal #	Title	Spokespersons	Collaborating Institutions	Status
#911	A Systematic Study of π^+ and π^- Scattering to 2_1^+ States in Ni, Zn, Ge, and Se	J. D. Zumbro, S. J. Seestrom- Morris, and H. T. Fortune	University of Minnesota, University of Pennsylvania, University of Texas at Austin, and Los Alamos National Laboratory	Status: 120 hours at B ⁺ priority data analysis
#959U	Inelastic Pion Scattering from ^{20}Ne	S. Mordechai, C. Fred Moore, and H. T. Fortune	University of Texas at Austin, Ben Gurion University, Los Alamos National Laboratory, and University of Pennsylvania	Status: 200 hours at B priority data analysis
#1016U	Inelastic Pion Scattering from ^{27}Al and $^{28,29}\text{Si}$	M. Burlein and H. T. Fortune	Los Alamos National Laboratory, University of Pennsylvania, and University of Texas at Austin	Status: 250 hours at B ⁺ priority in queue
#1017U	Interference Effects in Non-analog Pion Double Charge Exchange	K. S. Dhuga and H. T. Fortune	Los Alamos National Laboratory, University of Pennsylvania, University of Texas at Austin, and New Mexico State University	Status: 300 hours at B ⁺ priority for one angular distribution queue
#1025U	Pion Elastic and Inelastic Scattering from Polarized ^{13}C	G. R. Burleson and D. Dehnhard	New Mexico State University, University of Texas at Austin, University of Minnesota, University of Pennsylvania, and Los Alamos National Laboratory	Status: one cycle at A ⁺ priority data analysis
#1028	Measurements of Double-Charge-Exchange and Elastic Scattering on ^{14}C and ^{16}O at Energies above the $\Delta_{3/2,3/2}$ Resonance	H. W. Baer, C. L. Morris, and G. R. Burleson	Los Alamos National Laboratory, New Mexico State University, and University of Texas at Austin	Status: 228 hours at A ⁻ priority data analysis

#1050 Search for double-dipole and dipole-analog excitations using pion double charge exchange

S. Mordechai, H. T. Fortune, and C. L. Morris

University of Texas at Austin, Ben Gurion University, University of Pennsylvania, and Los Alamos National Laboratory

Status: 228 hours at A⁻ priority data analysis

#1071U Study of Pion Absorption in ³He and ⁴He

C. S. Mishra, C. L. Morris, and R. D. Ransome

Los Alamos National Laboratory, Rutgers University, University of South Carolina, University of Maryland, New Mexico State University, University of Virginia, and University of Texas at Austin

Status: 350 hours at B⁺ priority in queue

#1081 Double charge exchange within the (f_{7/2})ⁿ shell-model space

H. T. Fortune, C. L. Morris, and J. D. Zumbro

University of Pennsylvania, New Mexico State University, Argonne National Laboratory, Los Alamos National Laboratory, University of Texas at Austin, and University of York

Status: 164 hours at B⁺ priority data analysis

#1083 Elastic scattering of π^+ and π^- from ⁴He at forward angles

D. Dehnhard

University of Minnesota, Los Alamos National Laboratory, University of Pennsylvania, and University of Texas at Austin

Status: 172 hours at A⁺ priority data analysis

#1103 Measurement of the ratio of (π^+ , $\pi^{+'}$) versus (π^- , $\pi^{-'}$) at T _{π} = 450 MeV on ¹³C, ¹⁴C, and ¹⁵N

A. Williams, S. Mordechai, and C. Fred Moore

University of Texas at Austin, University of Pennsylvania, New Mexico State University, and Los Alamos National Laboratory

Status: 100 hours at B⁺ priority data analysis

#1104 Study of the giant quadrupole resonance by high energy pion scattering

S. J. Seestrom-Morris

Los Alamos National Laboratory, and University of Texas at Austin

Status: 280 hours at B⁺ priority data analysis

#1105 (π , π' p) Coincidence Measurement above Particle Emission Threshold

Sung H. Yoo and Christopher L. Morris

University of Texas at Austin, University of Minnesota, University of Colorado, Louisiana State University, and Los Alamos National Laboratory

Status: 434 hours at B⁺ priority in queue

- #1106 Study of pion-nucleus elastic scattering at energies above the $\Delta_{3/2,3/2}$ resonance
 K. S. Dhuga and J. A. McGill
 George Washington University, University of Pennsylvania, Los Alamos National Laboratory, and University of Texas at Austin
 Status: 340 hours at A⁻ priority data analysis
- #1107U Studies of pion double charge exchange scattering at energies above the $\Delta_{3/2,3/2}$ resonance
 G. R. Burleson
 New Mexico State University, University of Texas at Austin, University of Pennsylvania, and Los Alamos National Laboratory
 Status: 500 hours at B⁺ priority in queue
- #1118 Isospin Splitting of Isovector Resonances in Pion Double Charge Exchange
 Shaul Mordechai and C. Fred Moore
 Ben Gurion University of the Negev, University of Texas at Austin, Los Alamos National Laboratory, and University of Pennsylvania
 Status: 400 hours at A⁻ priority data analysis
- #1125 Pion Elastic and Inelastic Scattering from Self-Conjugate Nuclei at 180 MeV
 Christopher L. Morris and C. Fred Moore
 Los Alamos National Laboratory, and University of Texas at Austin
 Status: 400 hours at B⁺ priority in queue
- #1138 Pion Scattering to 6⁻ Stretched States in ³²B. L. Clausen and R. A. Lindgren
 Institute of Nuclear and Particle Physics and Physics Department,
 University of Virginia
 Status: 200 hours at A⁻ priority running
- #1140 Search of η^0 component in π -DCX
 C. L. Morris and C. F. Moore
 Los Alamos National Laboratory, University of Texas, and University of Pennsylvania
 Status: 212 hours at A⁻ priority in queue
- #1143 Study of pion absorption in ⁶Li, ⁷Li, ⁹Be, ¹⁰B, and ¹¹Pb
 C. L. Morris, C. S. Mishra, and R. D. Ransome
 Rutgers University, Los Alamos National Laboratory, York University, Arizona State University, University of Texas at Austin.
 Status: 168 hours at B⁺ priority data analysis
- #1150 Search for double giant dipole excitations using (π^- , π^+) pion double charge exchange
 S. Mordechai and C. Fred Moore
 Ben Gurion University, Los Alamos National Laboratory, University of Texas at Austin, and University of Pennsylvania.
 Status: 400 hours at A⁻ priority in queue

- #1154 Properties of the giant dipole resonance built on the isobaric analog state
 S. Mordechai and C. Fred Moore
 Ben Gurion University, Los Alamos National Laboratory, University of Texas at Austin, and University of Pennsylvania.
 Status: 400 hours at B⁺ priority data analysis
- #1167 Pion single charge exchange as a pathways for double charge exchange
 C. Fred Moore and R. J. Peterson
 University of Texas at Austin, University of Colorado
 Status: approved to be determined
- #1161 Double Charge Exchange on Se Isotopes
 H. T. Fortune, A. Fazely, and S. Mordechai
 University of Pennsylvania, Louisiana State University, University of Texas at Austin, Ben Gurion University, and Los Alamos National Laboratory
 Status: 200 hours at B priority data analysis
- #1186 Search for double giant Gamow-Teller excitations using pion double charge exchange
 S. Mordechai and C. Fred Moore
 Ben Gurion University, Los Alamos National Laboratory, University of Texas at Austin, and University of Pennsylvania.
 Status: 400 hours at B⁺ priority in queue
- #1187 Search for the Gamow-Teller resonance in pion single charge exchange
 S. Mordechai, C. L. Morris, and C. Fred Moore
 University of Texas at Austin, University of Colorado
 Status: 400 hours at B⁺ priority in queue
- #1193 Search for narrow structures at high excitation energies in nuclei
 A. B. Kurepin, C. L. Morris, and C. Fred Moore
 USSR Institute for Nuclear Research, Los Alamos National Laboratory, and University of Texas at Austin
 Status: approved in queue
- #1209 Energy dependence of double giant resonances in pion DCX
 S. Mordechai and C. Fred Moore
 University of Texas at Austin and Los Alamos National Laboratory
 Status: 250 hours at B⁺ priority in queue
- #1210 Study of the mechanism for DCX to excite analogs of anti-analog in heavy nuclei
 C. L. Morris, C. Fred Moore, and S. Mordechai
 University of Texas at Austin and Los Alamos National Laboratory
 Status: 150 hours at B⁺ priority in queue

#1211 ($\pi, \pi' X$) Coincidence measurement on and below the $\Delta_{3,3}$ resonance

J. L. Langenbrunner, D. Dehnhard, and S. H. Yoo

University of Minnesota, Los Alamos National Laboratory, University of Texas at Austin, and Rutgers University

Status: approved

to be determined

4 Work in Progress

Work reported in this section is based on preliminary results.

4.1 Isospin splitting of the giant dipole built on the isobaric analog state

4.1.1 Introduction

In a recent work[1,2,3,4] we reported the first observation of giant dipole resonances built on isobaric analog states (GDR $\otimes$ IAS) via pion DCX. In a mathematical notation these resonances can be written in terms of charge-exchange dipole and isospin-lowering operators acting sequentially on the ground-state wave function.[1] In the present work we report on the recent measurement of the isospin splitting of these new modes of excitations in the case of DCX on ^{93}Nb , and we give a brief description of the results and the theoretical analysis. Figure 1 shows a schematic energy-level diagram of analog, dipole, and the GDR $\otimes$ IAS observed in single and double charge exchange. The three isospin components of the charge exchange GDR and the GDR superimposed on the IAS are indicated. The predicted energy splitting and strength ratios of the members are discussed later.

4.1.2 Experiment

Experiment #1118 was performed with the energetic pion channel and spectrometer (EPICS) at the Clinton P. Anderson Meson Physics Facility (LAMPF) using the pion DCX setup.[5] Measurements were taken on a ^{93}Nb monoisotopic target of areal density 1.7 g/cm^2 at $T_\pi = 292 \text{ MeV}$ and scattering angles $5^\circ \rightarrow 30^\circ$ in 5° steps. Electrons were eliminated using a freon-gas Cherenkov detector in the focal plane. A set of veto scintillators separated by graphite wedges in the focal plane was used to reject muons.[6] The system was fine-tuned by placing aluminum absorbers of variable thickness in front of the first scintillator. The remaining background was pions resulting from continuum DCX on the target. The choice to run with the highest beam energy available at EPICS ($T_\pi = 292 \text{ MeV}$) results in a lower background level from the continuum DCX spectra since the excitation energy region of interest is away from the inclusive DCX peak. In addition, at this beam energy a large outgoing energy range ($\simeq 50 \text{ MeV}$) is covered by the acceptance of the spectrometer in a single setting. The variation of the spectrometer acceptance across the focal plane was measured by pion scattering from ^{12}C .

4.1.3 Discussion of the data

Figure 2 shows the ^{93}Nb on-line missing-mass spectrum at 10° . In addition to the DIAS transition at $E_x = 19.3 \text{ MeV}$ ($Q = -21.9 \text{ MeV}$) the spectrum shows the existence of two wide peaks labeled GR1 and GR2 very high in the continuum region at about 13.9 and 18.0 MeV above the DIAS. The spectra have been corrected for the measured variation of the spectrometer acceptance as a function of momentum. Based on the angular distribution

of the resonance and the $A^{-1/3}$ dependence of the excitation energy from many other targets[2] the resonance was interpreted as a giant dipole built on the isobaric analog state (GDR $\otimes$ IAS).[3,4] In Fig. 2 we fit the spectra with $\Gamma(\text{GR1}) = 3.3$ and $\Gamma(\text{GR2}) = 2.0$ MeV. These values give the best fit to the data. The spectra can be well fitted using a Lorentzian line shape of variable width for the GRs. For the DIAS only a Gaussian shape was assumed, because its width arises almost entirely from experimental resolution. The background (dashed line) that arises from the DCX cross section to discrete low-lying states and to the continuum was fitted with a four-parameter polynomial function of the form, $\text{Background}(E) = R(1) + R(2)E + R(3)E^2 + R(4)E^3$, where E is the negative of the Q value.

4.1.4 Discussion

The splitting of the GDR $\otimes$ IAS can in general arise from three different sources:

- (a) **Deformations effects:** In deformed nuclei with axial symmetry, a dipole splits into two components arising from vibration along the major and minor axis of the nucleus.
- (b) **Spin coupling:** For nuclei with $J_f \geq 1$, the GDR splits into three members with $J_f = J_i - 1$, J_i and $J_i + 1$. In the simplest case of even-even target nuclei the GDR $\otimes$ IAS has a *single* J^π value of 1^- .
- (c) **Isospin splitting:** For $T \geq 1$ target nuclei, the charge exchange dipole splits into three members with $T - 1$, T , and $T + 1$.

In the present case ^{93}Nb is known to be a spherical nucleus so no splitting is expected from deformation effects. It is also known from photonuclear measurements that spin coupling does not contribute to the photonuclear peak.

For $T \geq 1$ target nuclei, a charge-exchange GDR built on the IAS will split into three components with isospin $T-1$, T , and $T+1$ arising from coupling of one unit of isospin to a state with isospin T (Fig. 1). Simple isospin geometry arguments predict relative strengths for the GDR $\otimes$ IAS members:[3,4]

$$\sigma(T-1) : \sigma(T) : \sigma(T+1) = \frac{(2T-1)(T-1)}{T(2T+1)} : \frac{(2T-1)}{T(T+1)} : \frac{3}{(2T+1)(T+1)} \quad (1)$$

These ratios are quite different from the ratios expected for a GDR in SCX, where the GDR is in a $T_z = T - 1$ nucleus. For $T = 11/2$, Eq. 1 gives the ratios 0.68:0.28:0.04 respectively. Therefore the GDR $\otimes$ IAS on ^{93}Nb should split mainly into two components since the upper member has a negligible strength. This is in close agreement with the observed ratios of $\sigma_+/\sigma_- = 0.37$.

A general treatment of isospin splitting in terms of isovector and isotensor potentials[7,8] gives the following relations for the energy splittings $\Delta E^+(T+1, T)$ and $\Delta E^-(T, T-1)$ for collective isovector states:

$$\Delta E^+ = (T+1)[E_v + (2T-1)E_t] \quad (2)$$

$$\Delta E^- = T[E_v - (2T + 3)E_t] \quad (3)$$

where E_v and E_t are the isovector and the isotensor energies. Using the values $E_v = 0.54$ MeV and $E_t = -0.001$ gives $\Delta E^- = 2.64$ MeV, $\Delta E^+ = 3.19$ MeV. This is in good agreement with the measured energy splitting of about 4 MeV in the present experiment. Data replay and analysis are now in progress for this experiment.

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Figure Captions

Figure 1: Schematic energy-level diagram of analog and dipole states observed in single and double charge exchange. The listed Q values refer to the case of DCX on ^{93}Nb .

Figure 2: Missing-mass spectrum for (π^+, π^-) reaction on a ^{93}Nb target at $T_\pi = 292$ MeV and $\theta_{lab} = 10^\circ$. The arrows indicate the fitted location of the DIAS and the giant resonances. Short vertical lines represent the statistical uncertainty of the data. The dashed line is the fitted background with a polynomial shape and the solid line is the fit to the spectrum using NEWFIT.

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4.2 Pion DCX above the $\Delta_{3/2,3/2}(1232)$ resonance

4.2.1 Introduction

This experiment continues the recently-initiated program of measurements of high-energy pion-nucleus double-charge-exchange scattering (DCX), which is being carried out in the P³ Channel with the Large-Acceptance Spectrometer (LAS). At present this system provides the only facility for DCX measurements for 300–550 MeV incident pion kinetic energies. Measurements have been made of cross sections for (π^+, π^-) scattering at several energies in this range on ^{12}C , ^{26}Mg , $^{42,44,48}\text{Ca}$, $^{46,50}\text{Ti}$, ^{52}Cr , $^{54,56}\text{Fe}$, ^{80}Se , ^{90}Zr , ^{197}Au and ^{208}Pb . These include transitions to double isobaric analog states (DIAS) as well as nonanalog transitions to residual ground states for $T > 1$ nuclei. For many ground-state transitions, only upper limits have been found.

4.2.2 Experiment

Cross sections for DIAS transitions in $^{42,44,48}\text{Ca}(\pi^+, \pi^-)^{42,44,48}\text{Ti}$ at $\theta_{\text{lab}} = 5^\circ$ are presented in Fig. 1. The data are characterized by a relatively flat energy dependence, which is consistent with the behavior previously observed[1] for ^{14}C and ^{18}O , as well as for other nuclei, in this energy range. At 500 MeV, 5° cross sections were measured for DIAS transitions in ^{26}Mg , ^{56}Fe , ^{90}Zr , ^{197}Au , and ^{208}Pb . These, along with those for ^{14}C , ^{18}O and $^{42,44,48}\text{Ca}$ at 500 MeV, are shown in Fig. 2. This figure also displays the 450 MeV cross sections for $^{46,50}\text{Ti}$, ^{52}Cr , and ^{54}Fe , which are included under the assumption that the cross sections for these nuclei are also relatively flat between 400 and 500 MeV. These data are presented as the cross section $d\sigma/d\Omega$ divided by $(N-Z)(N-Z-1)$ as a function of mass number A , where $(N-Z)(N-Z-1)$ represents the product of the number of valence neutrons available for sequential single-charge-exchange scattering. The behavior of these cross sections can be well described by an $A^{-7/3}$ dependence, as shown by the solid lines in

Fig. 2. For energies ranging between 100 and 300 MeV, an overall $A^{-10/3}$ dependence was previously found, with the $T = 1$ targets appearing to have an $A^{-7/3}$ dependence when taken alone.[2] The lowered A -dependence at higher energies suggests a weakening of the strength of the DCX interaction, as might be expected from the smaller pion-nucleon total cross sections here.

Cross sections for the seven $f_{7/2}$ -shell nuclei have been compared to a two-amplitude model[3,4] which has successfully been used to fit similar measurements for energies below 300 MeV.[5] This model describes the DCX process for nuclei with excess neutrons within a single shell in terms of two amplitudes, usually denoted A and B . The A amplitude corresponds to transitions through analog states and involves long-range effects without nucleon correlations. The B amplitude arises from short-range correlations and represents transitions through, or to, nonanalog states. While the model was originally based on seniority-zero wave functions, corrections can be applied which correspond to the use of more realistic full shell-model wave functions and to account for A_{tgt} -dependent distortion effects. The model provides expressions both for DIAS cross sections and for nonanalog ground-state cross sections.

We have successfully fitted the DIAS cross sections for $^{42,44,48}\text{Ca}$ plus ^{50}Ti and ^{52}Cr with this model, but we have found that it significantly overpredicts the ground-state cross sections for all $T > 1$ nuclei. We also found that DIAS cross sections for the $T = 1$ nuclei ^{46}Ti and ^{54}Fe cannot be fitted together with that for ^{42}Ca , another $T = 1$ nucleus. These results are qualitatively the same whether or not corrections are applied. Considering the success of this model at lower energies, its failure in this energy range is surprising. Further work, both experimental and theoretical, may give some insight into these discrepancies.

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Figure 1: The 5° cross sections as a function of energy for the DIAS transition in $^{42,44,48}\text{Ca}$.

The filled circles are the new measurements reported here and the open circles are from previous work.

Figure 2: Small-angle differential cross sections at 500 MeV for the DCX reaction to analog states, divided by $(N-Z)(N-Z-1)$, as a function nuclear mass number A . Some 450 MeV data points for nuclei with A between 42 and 54 are also included. The filled circles represent $T = 1$ nuclei and the open circles represent $T > 1$ nuclei. The solid lines represent an $A^{-7/3}$ dependence.

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4.3 Pion scattering from polarized ^{13}C target

4.3.1 Introduction

The purpose of LAMPF Experiment #1025 was to measure the left-right scattering asymmetry parameter A_y from $\pi^\pm$ elastic and inelastic scattering from a polarized ^{13}C over an angular range of 30° to 100° at an energy of 162 MeV. This should better resolve the spin-flip component of pion scattering from this nucleus in the regime of the $\Delta_{3/2,3/2}$ resonance.

In general the pion-nucleus interaction can be written in the form:

$$f(\theta) + i g(\theta) \vec{n} \cdot \vec{\sigma} \quad (4)$$

where $\vec{n}$ is a unit vector perpendicular to the scattering plane, $\vec{\sigma}$ is the spin of the target nucleus, θ is the scattering angle, f is the non-spin-flip part of the reaction amplitude, and g is the spin-flip part of the interaction. The elastic cross section from an unpolarized target is given by:

$$\frac{d\sigma}{d\Omega} = |f|^2 + |g|^2. \quad (5)$$

Therefore the elastic scattering from a spin 1/2 nucleus involves both a large $\Delta S = 0$ and a small spin-dependent $\Delta S = 1$ amplitude. From measurements on unpolarized targets, one cannot extract unambiguously the spin-dependent cross section. Measurements and in particular asymmetry measurements on polarized targets are much more sensitive to the spin-flip amplitude of the pion-nucleus interaction.

The asymmetry parameter A_y is defined by:

$$A_y = \frac{1}{P_T} \frac{N^+ - N^-}{N^+ + N^-} = \frac{2 \operatorname{Im}(fg^*)}{|f|^2 + |g|^2} \quad (6)$$

where P_T is the polarization of the target nuclei and $N^\pm$ is the scattering yield from the two directions of spin. Measurement of A_y on polarized targets should reveal the interference

between the non-spin-flip scattering amplitude f and the spin-flip scattering amplitude g . Thus A_y should be more sensitive to the relative magnitude of the spin-flip component g .

4.3.2 Experiment

The basic approach to obtaining the asymmetry measurement of A_y was to take a data set of pion momentum loss at one particular angle and one nuclear spin polarity. The spin polarity was then reversed and the measurement repeated. A simple channel by channel subtraction of the two different spin polarity missing mass histograms would then yield the asymmetry parameter. In this way the unpolarized background should simply subtract out. Experimental background data was needed to determine errors and to find other effects (*i.e.*, a changing liquid level in the ^3He refrigerant in the target cell) due to reversing the spin polarity.

The EPICS spectrometer at LAMPF was chosen for this experiment because of its instrumental resolution of < 150 KeV. High instrumental resolution was needed to resolve the various inelastic states because of the additional loss of overall energy resolution due to presence of the cryostat materials intersecting the incident and scattered pions.

Toluene (C_7H_8) was chosen as the material for the polarized ^{13}C target because it contains no oxygen as the various alcohols used in past experiments do. There is less background near the ^{13}C inelastic states without the presence of oxygen and thus less error in the measurement. The polarization of ^{13}C in toluene was found to be $\approx 17\%$ using a 2.5 Tesla magnetic field and at a temperature of 450 milli-Kelvin, while for a substance such as butanol containing ^{13}C , the ^{13}C polarization is approximately 30%. What was lost in the lower polarization of toluene was balanced by the lower background due to the absence of oxygen. It was found after the experiment began that the target material was contaminated by 12% by weight of ^{12}C . ^{12}C should be easier to subtract from background

than ^{16}O because of its well defined states and should have little affect upon the asymmetry measurement since it will not polarize. The ^{12}C contaminant did mean that there was a reduction in 12% of ^{13}C in the target and thus decreased the scattering yield from polarized ^{13}C nuclei. At this point in the experiment it was too late to replace the contaminated target material with a more pure ^{13}C material due to time needed to obtain new material and the expense.

The ^{13}C toluene target was polarized using the dynamic nuclear polarization (DNP) technique. In principle, DNP works by placing the material to be polarized in a magnetic field (2.5 Tesla) and a cold temperature (450 milli-Kelvin). By driving the electron spin alignment with microwaves, the electron spin will couple to the nuclear spin in the substance and thus the flipping of spins of the electrons will drive the spin alignment of the nuclei. The driving microwave frequency is determined by the difference in the energy levels of the two nuclear spin states.

The toluene target material was doped with a small amount of a paramagnetic substance (DTBN) to increase the number of free electrons and then frozen into small beads by dripping it into a liquid nitrogen bath. The beads were placed into a copper target cell (3.5 cm by 6.0 cm by 0.8 cm) and then inserted into the ^3He cryostat. The material was cooled to 450 milli-Kelvin and placed in a 2.5 Tesla magnetic field. Microwaves of the frequency determined by the desired spin state were then applied. The material usually took about an hour to reach a polarization of around 15% and would eventually maximize at about 17%. To reverse the spin state, the microwaves and the magnetic field were turned off. After waiting a few minutes for the polarization to die out, the magnet would be turned back on and microwaves of the other polarization state would be applied to the target.

LAMPF Experiment #1025 began its run on 5/28/90 and finished on 7/24/90. Mea-

measurements were made at 30, 40, 50, 60, 75, and 90° for both $\pi^\pm$ and spin up/down at an energy of 162 MeV incident pi. This energy was chosen because a very extensive measurement of unpolarized ^{13}C cross section angular distribution had been done in the past at this energy.

Several unpolarized targets were used for calibration of the spectrometer and for background subtraction. To calibrate the ray tracing of the spectrometer, a target consisting of three vertical ^{12}C rods and a target consisting of three horizontal ^{12}C rods were used. To map out the momentum acceptance of the spectrometer and channel a ^{12}C slab target and a thin ^{93}Nb target were used. For an experimental reference spectra, short data runs were done on an unpolarized ^{13}C slab at each of the angles and incident pion polarity. For background subtraction, two dummy target cells were used. One within the cryostat that was an approximate duplicate of the actual polarized target cell and which also contained ^3He . The other dummy target was at room temperature outside of the cryostat and duplicated the metal and other solid components of the actual target cell and cryostat. A ^{12}C slab target was used to aid in subtraction of the background due to the ^{12}C contaminant in the polarized target material.

The first figure is a comparison of a polarized ^{13}C target on-line missing mass spectra with an unpolarized ^{13}C slab target spectra at the same angle. These spectra were made with a pion beam polarity of minus and at the lab scattering angle of 90°. The ground state and several inelastic states are easily identifiable in the polarized target spectra. No background was subtracted.

The second figure compares a raw spectra from the just completed Experiment #1025 at EPICS using ^{13}C toluene with a spectra from last year's Experiment #1025U at LEP with the ALAS spectrometer, having an instrumental resolution of 2.3 MeV and using a ^{13}C butanol polarized target. Experiment #1025U measured the asymmetry parameter

only for the elastic state at two angular distributions and over several excitation functions. Even though the #1025U spectra has been background subtracted for the copper target cell and for oxygen, the qualitative improvement in resolution and decreased ^3He background are easily seen. Most importantly is the easily discernible presence of the inelastic states in the Experiment #1025 spectra. This reflects the use of a high resolution spectrometer, the increase in target size, placing the target at the half-angle, and the elimination of some of the background. The third figure is a preliminary angular distribution from Experiment #1025U (presented by Yi-Fen Yen at the 1990 Paris conference). This shows that a non-zero asymmetry is present in $\pi^\pm$ scattering from ^{13}C for the elastic state. Results from Experiment #1025 should improve upon this.

4.3.3 Status

Data analysis and reduction is now in progress for Experiment #1025. Presently a 1.2 Mev FWHM resolution is seen. First an attempt to improve the energy resolution by better optimizing the ray tracing polynomials will be done. The asymmetry parameter for hydrogen will then be extracted. The asymmetry of hydrogen is accurately known and so this information will be compared to the experiment's NMR data to better determine the polarization of the target. Extraction of the elastic state and then the various inelastic states will follow.

Figure 1: Comparison of online spectra from E1025 polarized ^{13}C in cryostat missing mass spectra with unpolarized ^{13}C slab missing mass spectra. Both are at 90 degrees 162 MeV using pi minus. Background is not subtracted.

Figure 2a: Online spectra from E1025 polarized ^{13}C in cryostat missing mass spectra. At 90 degrees 162 MeV using π^- . Background not subtracted. Toluene target. Same as Figure 1, only scale changed.

Figure 2b: Replayed spectra from E1025U polarized ^{13}C in cryostat missing mass spectra. At 92 degrees 165 MeV using π^- . Cryostat and oxygen background subtracted. Butanol target.

$$^{13}\vec{\text{C}}(\pi^-, \pi^-)^{13}\vec{\text{C}} \quad T_\pi = 132 \text{ MeV}$$

Figure 3: Left-right asymmetry parameter A_y for polarized ^{13}C ground state from E1025U.

4.4 6^- stretched configuration on ^{32}S

4.4.1 Introduction

Stretched transitions are transitions with the highest angular momentum allowable in a single-particle transition between two major nuclear shells. This feature ensures that the transition density is given by a simple particle-hole configuration, and thus experiment may be compared to models via a single spectroscopic amplitude[1,2,3]. Recently several isovector 6^- stretched states have been observed[4] in electron scattering from ^{32}S (see Figures 1 and 2).

Experiment 1138 seeks to exploit the simplicity inherent in stretched transitions by using the amplitudes extracted from electron scattering in DWIA analysis of pion scattering from ^{32}S .

4.4.2 Physical Motivation

It has been found that the ratio of spectroscopic amplitudes extracted from DWIA analysis of pion scattering to amplitudes extracted from electron scattering varies significantly from nucleus to nucleus and even between transitions in a single nucleus[5]. The nucleus ^{32}S is unique in being self-conjugate and having several strong observed isovector transitions and thus affords the opportunity to make comparisons independent of uncertainties in pion DWIA theory. Also, Experiment 1138 will allow comparison with M6 strengths in ^{28}Si , where the amplitude ratio is close to unity.

Experimentally determined total isovector spectroscopic strengths run about one third the values deduced from using a simple particle-hole model [6]. Isoscalar strengths run even less, around 10 to 15 percent of that allowed by a particle-hole model[7]. A stretched transition in a self-conjugate nucleus is expected to be either purely isovector or purely isoscalar. Experiment 1138 is expected to find isoscalar transitions in addition to the ten

isovector transitions seen in electron scattering, and thus may provide interesting new data for explaining this quenching.

RPA calculations predict only one strong M6 isovector transition in the self-conjugate *sd* shell nuclei ^{24}Mg , ^{28}Si , and ^{32}S [8]. This agrees with experiment for ^{24}Mg and ^{28}Si , but disagrees for ^{32}S as shown in Figure 1. Fragmentation has also been seen to increase between ^{28}Si and ^{32}S for M1 strength[9]. It will be interesting to see whether ^{32}S isoscalar strength is similarly fragmented.

Pion scattering to stretched states which are purely isovector or purely isoscalar are expected to give σ^-/σ^+ ratios of unity. Exceptions to this are sometimes thought of as due to differences in binding for barely bound neutrons and protons[5]. The nucleus ^{32}S provides examples of a stretched state with all nucleons bound, stretched states with the proton unbound, and stretched states with both nucleons unbound.

Finally, the M6 stretched states are important because M4 stretched transitions in self-conjugate nuclei exist in only a few nuclei, and M6 transitions have small cross-sections.

4.4.3 The Experiment

The EPICS facility at LAMPF is unique in providing the resolution necessary to do this experiment. An elemental isotopically enriched ^{32}S target is available with an areal density of 100 mg/cm². The sulfur is held in place with 1 mg/cm² of aluminized mylar. The experiment was approved to run for 200 hours, and ran smoothly during August 1990. On-line data is presented in Figure 3.

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Figure Captions

Figure 1: Data from recent electron scattering[4] on ^{32}S . The data is at 154 degrees and 209 MeV. The excitation energy assignments are tentative.

Figure 2: Preliminary angular distributions from electron scattering to several ^{32}S stretched states[4].

Figure 3: On line histograms from Experiment 1138 showing some of the 6^- stretched configurations excited in pion inelastic scattering at $T_\pi = 162$ MeV and $\theta_{lab} = 75$ degrees. The top is for positive pions and the bottom is for negative pions. The horizontal scale is $-Q \times 100$ MeV.

Figure 1

Figure 2

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4.5 Energy dependence of the pion absorption cross section on ^{12}C

4.5.1 Introduction

It is generally believed that the excitation function for pion absorption on nuclei at incident pion energies from 20 to 140 MeV is a smoothly varying function of incident pion energy dominated by the delta resonance peak. In fact, very little data actually exists to support such a conjecture, and even high accuracy measurements of the fundamental pion absorption reaction $\pi^+ + d \rightarrow p + p$ suggested structure at energies around 30 MeV[1]. There also have been suggestions[2,3,4] that the pion production yields from heavy targets bombarded by protons could indicate a deviation from a smooth energy dependence at approximately 30 MeV. Definitive evidence for any anomalous energy dependence has been lacking.

Recent data from Akimov *et al.*[4] indicated the presence of a dip in the pion absorption excitation function of ^{12}C in the energy region from 20 to 30 MeV. The observed structure appeared to be about 3 MeV in width, centered at around 28 MeV. If correct, this data would necessitate a review of theories of pion absorption and production, since no such narrow structures are predicted in conventional theories of the process.

4.5.2 Experiment

We have taken measurements which will provide a check on of the dip in the excitation function of ^{12}C as seen by Akimov *et al.* The measurements were made with the bismuth germanate ball ("BGO ball") detector at the Clinton P. Anderson Meson Physics Facility Low Energy Pion (LEP) channel. The details of the BGO ball are discussed elsewhere[6], and only the salient features for this experiment are reviewed here. The BGO ball consists of 30 phoswich detectors, whose faces form a truncated icosahedron with two opposing

faces missing to allow for the entry and exit of the incident beam. Thus, the detection solid angle subtended is $30/32$ of 4π sr. The individual phoswich detectors have a 3 mm plastic scintillator optically coupled to the front of a 5.6 cm bismuth germanate scintillator. This scintillator combination permits excellent charged particle identification and neutral detection.

The LEP channel was operated in a standard manner to provide pion beams with incident energies in 10 MeV steps from 20 to 140 MeV. Additionally, beam energy was also changed in finer energy steps between 20 and 40 MeV, and a 16 MeV beam was also used. The beam was focused onto a 20 cm long tungsten collimator with a 1.0 cm diameter aperture upstream of the BGO ball. The beam was monitored by a 5×5 mm² deuterated plastic scintillator placed in front of the target. The deuterated scintillator provided an absolute monitor of the total beam flux, a measurement of the relative pion content of the beam, and an accurate energy calibration via the reaction $\pi^+ + d \rightarrow p + p$ for the elements of the BGO ball. A large veto scintillator downstream from the ball was used to veto events which resulted from particles which failed to be removed from the beam by interactions with the target. Beam fluxes, typically ranging from around 10^4 /s at the highest energies to about 300/s at 16 MeV, were limited to reduce singles rates in the BGO crystals to less than 2×10^4 /s.

A CD₂ target 1 cm² and 500 ± 10 mg/cm² thick was placed at the center of the ball. This target was attached to and held in place by a paper cylinder attached to a polyethylene shell in the shape of the missing downstream element of the ball. The deuterium in the target provided additional deuterium target nuclei for the energy calibration described above. The target holder provided only a small background to the measurements reported here as verified by several measurements using a blank target holder at several energies, typically less than 3%.

Laboratory total cross sections for the solid angle subtended by the ball were determined from the total inclusive two-proton yield measured in the ball with the deuterium contribution subtracted. The cross sections determined at 50, 100, and 150 MeV are in agreement with previous measurements[6]. The cross sections generally have an overall absolute normalization uncertainty of about 15%; the relative normalization uncertainty was much smaller, typically limited by the knowledge of the pion fraction in the beam.

The excitation function shown in Fig. 1 exhibits a smooth increase in yield for energies above 40 MeV. In Fig. 2 are the data of Akimov *et al.*; the data taken here are in general agreement with the data from that work. Since the two data sets arise from different experiments using different targets and detection systems, it is unlikely that a systematic defect in either experiment accounts for the feature seen in Fig. 2.

4.5.3 Summary

The preliminary data taken in this work will serve as a check on the findings of Ref. 5 concerning a dip in the energy dependence of the pion total absorption cross section at 28 MeV with a width of approximately 3 MeV. Since such a structure is contrary to conventional wisdom concerning the absorption mechanism, the theoretical understanding of low energy pion absorption will require re-examination. As noted by Akimov *et al.*, it is important to determine if the same structure appears in the fundamental pion absorption reaction $\pi^+ + d \rightarrow p + p$. We are presently examining the deuterium data taken simultaneously with the carbon data to determine the answer to that question.

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Figure Captions

Figure 1: Excitation function for $^{12}\text{C}(\pi^+, 2p)$ for incident pion energies from 16 to 140 MeV measured in this work. Cut off at total energy of two protons equal to 50 MeV.

Figure 2: Excitation function for $^{12}\text{C}(\pi^+, 2p)$ measured in Ref. 5. Cut off at total energy of two protons equal of 70 MeV.

[AUSTIN.MORRIS.NMS.PROPOSAL]FIGURE10.PLOT

Fig.3 Total cross section vs pion kinetic energy
for all events with T_{pp} more than 70 MeV.
(in arbitrary units)

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