EXPERIMENTS IN INTERMEDIATE ENERGY PHYSICS

Final Report

May 1, 1979 and August 31, 2002

DOE Patent Clearance Granted
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February 2003

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This material is based upon work supported by the
U.S. Department of Energy under
Award No. DE-AC02-79ER10423 and
No. DE-FG02-87ER40362

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SUMMARY

Research in experimental nuclear physics was done from 1979 to 2002 primarily at intermediate energy facilities that provide pion, proton, and kaon beams. Particularly successful has been the work at the Los Alamos Meson Physics Facility (LAMPF) on unraveling the neutron and proton contributions to nuclear ground state and transition densities. This work was done on a wide variety of nuclei and with great detail on the carbon, oxygen, and helium isotopes. Some of the investigations involved the use of polarized targets which allowed the extraction of information on the spin-dependent part of the Δ -nucleon interaction. At the Indiana University Cyclotron Facility (IUCF) we studied proton-induced charge exchange reactions with results of importance to astrophysics and the nuclear few-body problem. During the first few years, the analysis of heavy-ion nucleus scattering data that had been taken prior to 1979 was completed. During the last few years we created hypernuclei by use of a kaon beam at Brookhaven National Laboratory (BNL) and an electron beam at Jefferson Laboratory (JLab). The data taken at BNL for a study of the non-mesonic weak decay of the Λ particle in a nucleus are still under analysis by our collaborators. The work at JLab resulted in the best resolution hypernuclear spectra measured thus far with magnetic spectrometers.

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1 Introduction

This is the final report on the research done under grant numbers DOE/DE-AC02-79ER10423 and DOE/DE-FG02-87ER40362 between the University of Minnesota and the Department of Energy. It covers 23 years of experimental nuclear physics research between 1979 and 2002. The principal investigator of the grants was Prof. D. Dehnhard.

The project title changed over the years:

1979 - 1981 “Nuclear Structure Studies with Pions and Heavy Ions”

1981 - 1984 “Nuclear Structure Studies with Pions and Light and Heavy Ions”

1984 - 1987 “Nuclear Structure Studies with Pions and Light Ions”

1987 - 1997 “Pion- and Proton-Nucleus Interactions at Intermediate Energy”

1997 - 2002 “Experiments in Hypernuclear Physics”

The research was done in collaboration with physicists from many different Universities and National Laboratories. In the last few years, collaborators were mostly from the following institutions: Brookhaven National Laboratory (BNL), Los Alamos National Laboratory (LANL), Hampton, Tohoku, and Carnegie Mellon Universities, and the Universities of Houston, Kentucky and Zagreb.

The following postdoctoral research associates contributed in various ways to the research: V. Shkolnik, D. B. Holtkamp, S. J. Seestrom-Morris, S. K. Nanda, M. A. Franey, S. M. Sterbenz, B. Brinkmoeller, M. Palarczyk, J. L. Langenbrunner, J. M. O'Donnell, J. Gerald, H. J. Juengst, and J. H. Liu. Prof. S. Chakravarti of California State University at Pomona provided help with the theoretical analysis of the data during several visits.

Publications in refereed journals, conference proceedings, abstracts submitted to recent meetings and other publications are listed in subsections 3.1 - 3.5. A list of advanced degrees granted to graduate students and the titles of their Ph.D. or Master of Science (M. S.) theses is given in subsection 4.

The research goals and results are discussed in the following section. Reprints of eleven publications in Physical Review Letters are attached as section 5.

2 Research Goals and Results

Over the period of 23 years, experiments in intermediate energy physics were carried out primarily at Los Alamos Meson Physics Facility (LAMPF), the Indiana University Cyclotron Facility (IUCF), the Brookhaven National Laboratory (BNL) and, most recently, the Jefferson National Accelerator Facility (JLab).

2.1 Work at LAMPF and IUCF (1979-1997)

At LAMPF, the main goal of the experiments was the study of nuclear structure using the unique selectivity of the interaction of positive and negative pions with nucleons with respect to the neutron-proton structure of nuclear ground states and of transitions to excited states. Specifically, the studies of elastic and inelastic pion scattering and single-charge exchange reactions on the carbon, oxygen, and helium isotopes provided new knowledge that was not attainable with conventional nuclear probes such as protons. The pion work was first carried out with unpolarized targets, later with polarized targets. Some of this work was recognized by a report in "Physics News 1979" [1] which is sponsored by the American Physical Society and presents summaries of important discoveries in a particular year. A summary of our research at LAMPF was also published in the CERN Courier[2].

At IUCF, our work on the (p, n) reaction on the helium isotopes yielded information for use in astrophysical models of mass accretion of neutron stars as well as on the structure of the mass four system and the quasifree processes that dominate the reactions on helium-3.

Highlights of our research at LAMPF and IUCF

- Discovery of nuclear excitations by pions consistent with pure neutron and pure proton transitions. Specifically, the transition to the first $9/2^+$ state in ^{13}C was found to arise only from the promotion of a neutron from the $p_{3/2}$ to the $d_{5/2}$ shell. PRL43(1979)1091.
- Transitions in the selfconjugate nucleus ^{16}O to three 4^- states showed large π^+/π^- asymmetries in inelastic pion scattering. These asymmetries were shown to arise from

three-state isospin mixing. PRL45(1980)420.

- Transitions involving a spin transfer of 1 were found to have distinctly different incident energy dependences than transitions with a spin transfer of 0. PRL46(1981)1447.
- The interference of proton and neutron transition amplitudes, for example for transitions to 2^+ and 4^- states in ^{14}C , leads to vanishingly small cross sections for π^+ scattering and strongly enhanced cross sections for π^- scattering or vice versa. PRL37(1981)216.
- Only a small amount of isospin mixing was found in pion scattering from ^4He . This result is in striking contrast to the large amount of isospin mixing inferred from the photonucleon cross section ratio, $\sigma(\gamma, p)/\sigma(\gamma, n)$. PRL57(1986)543.
- Our comprehensive data set for $\pi - ^4\text{He}$ elastic scattering uncovers inconsistencies between existing data sets and allows a determination of $\pi - ^4\text{He}$ phase shifts. PRC44(1991)2031.
- π^+/π^- cross section ratios for proton and triton knockout reactions on ^4He cover a large range of values between 0.3 and about 50 in contrast to the expected values between 6 and 8. The results are interpreted as due to interference effects. PRC46(1992)52 and PRL69(1994)1508.
- First measurement of neutron spectra from the $^4\text{He}(p, n)^4\text{Li}$ reaction at intermediate energies resolve the controversy over the existence of narrow structures in ^4Li . This experiment provides the data needed by current astrophysical models of solar flares and of the mass accretion of neutron stars. PLB369(1996)39.
- First measurement of asymmetries in pion scattering and pion-induced single charge exchange on polarized ^3He . Evidence is found for the importance of the Δ -neutron spin-spin interaction. PRL76(1996)3667, PRC56(1997)2607, and PRC60(1999)24001.

2.2 Work at BNL and JLab (1997-2002)

At BNL, we created hypernuclei using the kaon beam of the Alternating Gradient Synchrotron (AGS). Specifically, we studied the formation of the hypernucleus $^1_2\Lambda\text{B}$ using the (K^-, π^0)

reaction on ^{12}C (BNL experiment E907). The π^0 mesons were detected with the Neutral Meson Spectrometer (NMS). The analysis of E907 has been completed and a paper has been submitted for publication to Physical Review C.

In addition, we took data for a study of the nucleon-induced, non-mesonic weak decay of the Λ in the $^4_\Lambda\text{H}$ hypernucleus (BNL experiment E931). The formation of a $^4_\Lambda\text{H}$ by the (K^-, π^0) reaction on a liquid ^4He target was identified by the detection of the π^0 mesons with the NMS. The neutrons and protons from the decay of the residual hypernucleus $^4_\Lambda\text{H}$ were detected by large arrays of proton and neutron detectors.

The preparation and execution of E931 has been our major effort during the past 16 months. Postdoc Henry Juengst (HGJ) supervised the work on all aspects of the experiment, spending long time periods at BNL. Postdoc Jinghua Liu (JHL) performed calculations of simulations of beam and reaction particle detection devices that proved important in the planning of the experiments. During the last two beam periods all components of the very complex setup were working properly. These include numerous beam detection devices, the neutral meson spectrometer (NMS), arrays of neutron detectors and sets of timing scintillators and proton tracking chambers to detect the neutrons and protons from the nucleon-induced decay of the Λ , and, most importantly, the liquid helium target.

The responsibility of the analysis of the data has been taken on by the participants from Carnegie Mellon University (CMU). It will be the basis of a Ph.D. thesis of a CMU student. At the time of this report it is not possible yet to determine whether this effort has produced a result of the required accuracy.

In addition, we worked on the analysis of the high-resolution study of the electroproduction of $^1_0\Lambda^0$ using the $^{12}\text{C}(e, e' \text{K}^+)$ reaction at JLab (Experiment E89-009). JHL had been instrumental in the writing of the computer codes for taking and analyzing the data.

Due to the full-time commitment of HGJ to E931, no progress was made during the last 16 months on the analysis of existing data taken with the CEBAF Large Acceptance Spectrometer (CLAS) (E89-004). However, this work is currently being continued by HGJ

who is now a postdoctoral research associate at George Washington University.

Finally, we mention that during the first three years of the 23-year period, part of the effort was directed to completing the analysis of experimental data on heavy-ion induced reactions and scattering that had been taken with the MP Tandem accelerator at the University of Minnesota prior to 1979. In particular we cite the optical model study of elastic scattering of ^{16}O from ^{28}Si at many different incident energies. PRC28(1983)294.

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3 Publications

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1. “Experimental Study of the $^{12}\text{C}(K_{\text{stopped}}, \pi^0)^{12}\text{B}$ Reaction,” M. W. Ahmed, X. Cui, A. Empl, E. V. Hungerford, K. J. Lan, M. Youn, R. E. Chrien, R. Gill, P. Pile, A. Rusek, R. Sutter, J. Bjoraker, D. Dehnhard, J. M. O’Donnell, J. Gerald, H. Juengst, J. H. Liu, J. C. Peng, C. L. Morris, C. M. Riedel, H. A. Thiessen, D. Androic, I. Bertovic, M. Furic, T. Petkovic, M. Planinic, L. Tang, V. Zeps, R. J. Peterson, submitted for publication in Phys. Rev. C (2002).

2. "Energy Calibration of the CsI Crystals of the Neutral Meson Spectrometer (NMS) using Monoenergetic π^0 from the Decay of Stopped K^+ ," H. G. Juengst, M. Ahmed, D. Androic, R. Barber, I. Bertovic, J. Bjoraker, R. Chrien, D. Dehnhard, M. Furic, R. Gill, E. Hungerford, J. H. Liu, J. O'Donnell, J. Peng, P. Pile, C. M. Riedel, A. Rusek, M. Sarsour, R. Sutter, T. Vidnovic, M. Youn, V. Zeps, submitted for publication in Nuclear Instruments and Methods, 2002.
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3.3 Selected publications in conference proceedings

1. "Pion-Nucleus Interactions (Experiments)," D. Dehnhard, Proceedings Ninth International Conference on High Energy Physics and Nuclear Structure, Versailles, France, July 6-10, 1981, Nucl. Phys. **A374**, 377c (1982).
2. "Nuclear Structure Studies Using Pion Inelastic Scattering," D. Dehnhard and S. J. Seestrom-Morris (presented by D. D.), Proceedings International Symposium on Electromagnetic Properties of Atomic Nuclei, Tokyo, Japan, Nov. 1983, edited by H. Horie and H. Ohnuma, Tokyo Institute of Technology, p. 225 (1984).
3. "Anomalous Spin Response in the $^4\text{He}(\vec{p}, \vec{p}')^4\text{He}^*$ Reaction at 500 MeV", S. K. Nanda, S. M. Sterbenz, D. Dehnhard, M. K. Jones, C. E. Parman, Yi-Fen Yen, and K. W. Jones, Proceedings 8th International Symposium on High Energy Spin Physics, Minneapolis, MN Sept. 6-18, 1988, ed. by K. J. Heller. AIP Conf. Proc. No. 187, p. 681, N. Y. (1989).
4. "High Energy Kaon and Pion Scattering," B. Brinkmoller, D. Dehnhard, and S. Chakravarti, Proceedings Workshop on Science at the KAON Factory, TRIUMF, Vancouver, B. C., Canada, July 23-28, 1990.

5. "Pion Elastic Scattering on a Polarized ^{13}C Target," D. Dehnhard, Yi-Fen Yen, M. A. Franey, and S. Chakravarti (Presented by D. D.), Proceedings International Symposium on Mesons and Light Nuclei V, Prague, C.S.F.R., September 1-6, 1991, Few-Body Systems, Suppl. 5, 274 (1992).
6. "New results on spin effects in pion-nucleus scattering and single-charge exchange," D. Dehnhard, Proceedings of Meson'96 Workshop on Production, Properties and Interaction of Mesons, Cracow, Poland, May 10-14, 1996, Acta Physica Polonica **B 27**, 3019 (1996).

3.4 Abstracts submitted to recent meetings (1999 - 2001)

1. "Energy Calibration of the CsI Crystals of the Neutral Meson Spectrometer (NMS) Using the Monoenergetic π^0 from the Decay of stopped K^+ ," Henry Juengst on behalf of the E907 and E931 collaborations at BNL. 1999 Spring Meeting in Atlanta, paper VB04.11, Instrumentation for Nuclear Physics II.
2. "Recent Results from the Study of $^1_\Lambda\text{B}$ Levels Using the $(\text{K}_{\text{stopped}}^-, \pi^0)$ Reaction on ^{12}C ," Mohammad Ahmed on behalf of the E907 collaboration. 1999 Spring Meeting in Atlanta, paper IB04.08, Sub-Nucleonic Degrees of Freedom.
3. Electroproduction of hypernuclei at Jlab, Liguang Tang, Hampton University, E89-009 Collaboration, BAPS **45**, No. 5, page 59, paper ED-2. (DNP 2000 Fall meeting).
4. "Spectroscopic study of electroproduced light Λ hypernuclei," Y. Sato, Hampton University, E89-009 Collaboration, BAPS **45**, No. 5, page 87, paper KD-10. (DNP Fall 2000 meeting).
5. "Hypernuclear spectroscopic study at TJNAF," Jinghua Liu, University of Minnesota, E89-009 Collaboration, BAPS **46** (2001), No. 2, page 118, paper Q8-5. (APS April 2001 meeting).
6. "Photoproduction of hyperon resonances," Henry G. Juengst, CLAS Collaboration, BAPS **46** (2001), No. 2, page 118, paper Q8-1. (APS April 2001 meeting).

7. "Photoproduction of Hyperon Resonances on Hydrogen," Henry G. Juengst, University of Minnesota, CLAS Collaboration. Abstract submitted to the International Conference on Nuclear Physics, Berkeley, CA, July 30 to August 3, 2001.

3.5 Other publications

1. "Pion-nucleus interactions with high-energy pions", D. J. Ernst and D. Dehnhard, in PILAC Users Group Report on the Physics with PILAC, Los Alamos National Laboratory Report, LA-UR-92-150, 161 (1991).
2. "Pion probes", contribution to "Research at LAMPF", February 1992, prepared for presentation to the NSAC committee.

4 Advanced degrees granted

1. Susan J. Seestrom-Morris, Ph.D., Sept. 1981.

Title of Ph.D. Thesis:

"The structure of ^{13}C studied by pion scattering near the [3,3] resonance."

2. M. Garakani, M. S., June 1984.

Title of Master's Plan B paper:

"Pion scattering to the three lowest 2^+ states in ^{14}C ."

3. Charles L. Blilie, Ph. D., February 1985.

Title of Ph. D. Thesis:

"Pion scattering from ^4He ."

4. Li-Ping Lung, M. S., July 1986.

Title of Master's Plan B paper:

"Analysis of elastic and inelastic pion scattering from ^{48}Ca ."

5. C. E. Parman, M.S., December 1988

Title of Master's Plan B paper:

"The reaction ${}^4\text{He}(p,p'){}^4\text{He}$ at $T_p = 800$ MeV and analysis of the 0^+ , 20.1 MeV excitation".

6. Mark K. Jones, Ph.D., May 1989

Title of Ph.D. Thesis:

"Pion elastic scattering and the $(\pi, \pi p)$ reaction on ${}^4\text{He}$ in the Δ region."

7. Yi-Fen Yen, Ph. D., December 1991.

Title of Ph. D. Thesis:

"Pion elastic scattering from polarized ${}^{13}\text{C}$ in the energy region of the P_{33} pion-nucleon resonance."

8. Yi-Ju Yu, M. S., January 1993.

Title of Master's Plan B paper:

"Ray trace calculations for pion scattering experiments from polarized ${}^{13}\text{C}$."

9. Peter Yurek, M. S., August 1993.

Title of Master's Plan B paper:

"Feasibility of a measurement of asymmetries of the pion-induced single charge exchange reaction on polarized ${}^3\text{He}$."

10. Carla M. Edwards (Riedel), Ph. D., 1995.

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"Proton-induced charge exchange on Helium-4 at intermediate energies."

11. Michelle A. Espy, Ph. D., 1996.

Title of Ph. D. Thesis:

"Asymmetries for elastic scattering of charged pions from polarized Helium-3 at Delta resonance energies"

12. Brian Davis, M. S., 1996.

Title of Master's plan B paper:

"The (K_{stop}^-, π^0) reaction: A new tool in hypernuclear physics."

13. Jefferson Bjoraker, M.S. 1998.

Title of Master's plan B paper:

"Contributions to hypernuclear experiments at Brookhaven National Laboratory."

5 Reprints of eleven articles published in Physical Review Letters

Pure Neutron and Pure Proton Transitions in Inelastic Scattering of Pions by ^{13}C

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Differential cross sections $\sigma_{\pi^{\pm}}(\theta)$ for elastic and inelastic scattering of 162-MeV pions from ^{13}C were measured at momentum transfers between 0.6 and $2.1 \hbar \cdot \text{fm}^{-1}$. For two inelastic transitions, enhancement of $\sigma_{\pi^{-}}$ over $\sigma_{\pi^{+}}$ and of $\sigma_{\pi^{+}}$ over $\sigma_{\pi^{-}}$ were observed which are consistent with the values for pion scattering from free nucleons. The results are discussed qualitatively in terms of simple shell-model and weak-coupling-model configurations.

In nuclear structure physics, high-resolution and high-intensity intermediate-energy pion beams are presently being employed with increasing success. For example, recent comparative studies¹⁻⁴ of π^{+} and π^{-} scattering at pion energies near the $[3, 3]$ resonance yielded new information on differences between neutron and proton ground-state and transition densities. For inelastic scattering from nuclei with a neutron excess, measured²⁻⁴ cross-section ratios $R = \sigma_{\pi^{-}}(\theta)/\sigma_{\pi^{+}}(\theta)$ range from 0.8 to 1.9. These values are not as different from unity as the ratios for pion scattering from free nucleons: $R \approx \frac{1}{9}$ for protons and $R \approx 9$ for neutrons at the $[3, 3]$ resonance. This result is not unexpected for the collectively enhanced transitions in even- A nuclei on which current studies have concentrated.²⁻⁴ Results closer to the free-nucleon values may be obtained for odd- A nuclei in transitions between single-particle states or between states which differ only by a particle-hole excitation. The ^{13}C nucleus appears particularly well suited for such a study since it shows single-particle and collective features in a number of low-lying levels.⁵

We have therefore measured differential cross sections for elastic and inelastic scattering of π^{+} and π^{-} from ^{13}C at 162 MeV using the EPICS system⁶ at the Clinton P. Anderson Meson Physics Facility (LAMPF). The target⁷ was a 15-cm $\times$ 23-cm sheet of carbon, 210 mg/cm² thick, enriched in ^{13}C to 99%, and covered on both sides by thin (~ 1 mg/cm²) Kapton foils. The energy resolution for all scattering angles was better than 300 keV (full width at half maximum).

The most striking result of this experiment is the very large value, $R \sim 9$, for the transition to a state at 9.5 MeV. This result is consistent with the free π -neutron value of 9. At angles $\theta_{c.m.}$

$\geq 50^{\circ}$ and $T_{\pi} = 162$ MeV (momentum transfers $\geq 1 \hbar \cdot \text{fm}^{-1}$) we find this state quite strongly excited by π^{-} but so weak in π^{+} scattering that it is often difficult to discriminate from the background (Fig. 1). We also observe a significant enhancement of π^{+} scattering over π^{-} scattering for a group of states at about 16 MeV excitation. Around 21 MeV there are differences in the structure of the π^{+} and π^{-} spectra [Figs. 1(a) and 1(b)] quite similar to results of a recent experiment⁸ on ^{12}C . The centroid of this group of states is

FIG. 1. Summed normalized yield spectra (a) $Y_{\pi^{-}}$ and (b) $Y_{\pi^{+}}$ for $^{13}\text{C}(\pi^{\pm}, \pi^{\pm'})$ at $T_{\pi} = 162$ MeV ($\theta_{lab} = 62^{\circ}, 68^{\circ}, 74^{\circ}, 80^{\circ}, 86^{\circ}$), and (c) difference between $Y_{\pi^{-}}$ and $Y_{\pi^{+}}$.

shifted towards lower excitation energy in the π^+ spectra in comparison with the π^- spectra as is apparent in the difference spectrum [Fig. 1(c)].

We prefer to represent the differences between the cross sections σ_{π^-} and σ_{π^+} by the parameter $A = (\sigma_{\pi^-} - \sigma_{\pi^+}) / (\sigma_{\pi^-} + \sigma_{\pi^+})$ rather than by the ratio $R = \sigma_{\pi^-} / \sigma_{\pi^+}$. Values of A obtained at the maxima of the differential cross sections are presented in Fig. 2. For the 9.5-MeV state $A = +0.8 \pm 0.2$, consistent with a pure neutron excitation. For a state or a group of states at $E_x \approx 16$ MeV, $A = -0.6 \pm 0.2$ indicating an almost pure proton excitation. For other states the values of A range from about -0.4 to $+0.4$, more in line with previously observed enhancement factors. [The ratio $R = 1.86 \pm 0.16$ for $^{18}\text{O}(2^+)$ (Ref. 2) corresponds to a value of $A = +0.30 \pm 0.04$.]

Of the "single-neutron states" of ^{13}C known⁹ from $^{12}\text{C}(d, p)$ we resolve the weakly excited $\frac{1}{2}^+$ state at 3.09 MeV and obtain $A = 0.3 \pm 0.1$. The $\frac{5}{2}^+$ state at 3.85 MeV was not fully resolved from the $\frac{3}{2}^-$ state at 3.68 MeV but we estimate cross sections from peak fitting and derive $A = 0.4 \pm 0.1$. These values of A are only about one-half of the free-neutron value indicating sizable contributions from the protons or from more complex reaction mechanisms.

At forward angles ($\theta_{\text{c.m.}} \leq 50^\circ$) the unresolved triplet at 7.5 MeV is expected to be dominated by the transition to the collective $\frac{5}{2}^-$ state (7.55 MeV). This state and the $\frac{3}{2}^-$ state at 3.68 MeV are often interpreted as a weak-coupling doublet obtained by coupling a $p_{1/2}$ neutron to the first excited 2^+

state of ^{12}C . At forward angles the 3.68-MeV state is almost equally excited by π^+ and π^- ($A \approx 0$) but the 7.5-MeV triplet is a factor of 2 more strongly excited by π^+ than by π^- ($A = -0.3 \pm 0.1$). [At larger angles ($\theta_{\text{c.m.}} \gtrsim 50^\circ$) the 7.5-MeV triplet is nearly equally excited by π^+ and π^- .] The different values of A for the weak-coupling states imply a state dependence of the blocking of the quadrupole strength of ^{12}C by the extra neutron. This can be understood in terms of the major components of the wave functions in simple $j-j$ coupling. If the excited core (2^+ , $T=0$) consisted of only a $(p_{3/2})^{-1}(p_{1/2})^{+1}$ one-particle, one-hole (1p-1h) structure, the addition of a $p_{1/2}$ neutron would generate 2p-1h states with $J^\pi = \frac{1}{2}^-, \frac{5}{2}_1^-, \frac{5}{2}_2^-,$ and $\frac{3}{2}^-$. The isospin structure of the $\frac{1}{2}^-$, $\frac{3}{2}_2^-$, and $\frac{5}{2}_2^-$ states would be such that only protons could be involved in the transition. Apparently the "collective" $\frac{5}{2}^-$ state at 7.55 MeV has a large component of 2p-1h structure leading to the observed π^+ enhancement. Clearly the excited core is not a pure $[(p_{3/2})^{-1}(p_{1/2})^{+1}]_2^+$ state (1p-1h) and the experimental value of A for the $\frac{5}{2}^-$ state ($A = -0.3 \pm 0.1$) is smaller than the free-proton value. Thus neutrons must also be involved in the transition. The $\frac{3}{2}_1^-$ state can be reached by both proton and neutron excitations even if the core were a pure 1p-1h state. Still, the experimental value of $A \approx 0$ requires additional neutron contributions since the simple 1p-0h to 2p-1h transitions would favor proton excitations.

The spin and parity assignment, $J^\pi = \frac{3}{2}^-$, for the 9.5-MeV state is quite uncertain.^{5, 10-14} In low-energy electron scattering no $M1$ strength could be detected.¹⁰ Two- and three-particle-transfer reactions^{11, 12} quite strongly suggest a high-spin state at this energy and recent high-energy electron-scattering data¹³ yield $J^\pi = \frac{9}{2}^+$. A $\frac{7}{2}^+$ and a $\frac{9}{2}^+$ state have been predicted around this energy by Lane¹⁵ and later by several other authors (e.g., Baker¹⁶ and Jäger *et al.*¹⁷) as members of a weak-coupling multiplet based on a $d_{5/2}$ neutron coupled to the first excited 2^+ state in ^{12}C . Such a structure is consistent with the extremely small neutron width from $^{12}\text{C} + n$ elastic scattering¹⁴ and the preferential decay of the 9.5-MeV state in ^{13}C or its mirror at 9.0 MeV in ^{13}N by neutron or proton emission, respectively, to the 2^+ state in ^{12}C (see references in Ref. 12). The wave function of the $\frac{9}{2}^+$ member of the weak-coupling multiplet has a very large overlap with the wave function of a $\frac{9}{2}^+$ state at about 9.5 MeV predicted by the intermediate-coupling model (Ref. 18). A $\frac{9}{2}^+$ state of similar structure was

FIG. 2. Values of $A = (\sigma_{\pi^-} - \sigma_{\pi^+}) / (\sigma_{\pi^-} + \sigma_{\pi^+})$ from $^{13}\text{C}(\pi^\pm, \pi^\pm')$ at 162 MeV at the maxima of the differential cross sections. Broken horizontal lines: values of A for $\pi^+ + n$ and $\pi^+ + p$.

also found close to 9.5 MeV in a shell-model calculation.¹⁹

We remark that an inelastic transition to the $[(2^+, T_0=0) \otimes (d_{5/2})]_{1/2^+, \dots, 9/2^+, T=1/2}$ weak-coupling states should involve mainly neutrons. The ground state (g.s.) of ^{13}C may be represented by a mixture of p -shell $(m+1)$ -particle, m -hole states ($m=0, 1, 2$). If we assume the excited $^{12}\text{C}(2^+)$ to be a mixture of p -shell n -particle, n -hole states ($n=1, 2, 3, 4$) with $T_0=0$, the weakly coupled $d_{5/2}$ nucleon can only be a neutron. This means that only the promotion of a p -shell neutron to the $d_{5/2}$ shell can contribute to the transition if the g.s. and the multiplet states are connected by a single-particle operator. Thus the strong π^- enhancement for the 9.5-MeV state and the $\frac{3}{2}^+$ assignment from electron scattering¹³ suggest that this state is the $\frac{3}{2}^+$ member of the multiplet. The $\frac{7}{2}^+$ member²⁰ is probably the 7.59-MeV state of the unresolved triplet at 7.5 MeV. The π^+ enhancement of the 7.5-MeV triplet is observed only at forward angles ($\lesssim 50^\circ$). At larger angles ($\gtrsim 50^\circ$) the $\sigma_{\pi^+}(\theta)$ and $\sigma_{\pi^-}(\theta)$ are quite similar. This may be due to relatively large contributions from the $\frac{7}{2}^+$ state which should be enhanced in π^- scattering like the 9.5-MeV state.

Since we assume the $2^+ \otimes d_{5/2}$ configuration to be excited by a one-step process (primarily by the promotion of one of several $p_{3/2}$ neutrons to the $d_{5/2}$ shell), the transition can proceed by an orbital angular momentum transfer ΔL of at most 3. Thus the minimum total angular momentum transferred to the target, $\Delta J=4$, for the $\frac{1}{2}^- \rightarrow \frac{3}{2}^+$ transition, is obtained by a spin flip of the neutron. The shape of the angular distribution for the $\frac{3}{2}^+$ state has the appearance of a $\Delta L=5$ transition which we obtained from a spin-nonflip distorted-wave impulse-approximation (DWIA) calculation using the code²¹ DWPI with a complex collective form factor. However, angular distributions for spin-flip transitions are known²² to peak at larger angles than spin-nonflip transitions of the same ΔL . In fact, our qualitative arguments are being confirmed by recent microscopic DWIA calculations of Lee and Kurath²³ which use intermediate-coupling model wave functions¹⁸ for the g.s. and the lowest $\frac{3}{2}^+$ state. These calculations give a good fit to our data for the state at 9.5 MeV with $\Delta L=3$ and $\Delta S=1$.

States of a $2^+ \otimes d_{5/2}$ configuration can also be obtained by coupling a $d_{5/2}$ particle to a 2^+ , $T_0=1$ state of the core resulting in isospins $T=\frac{1}{2}$ or $T=\frac{3}{2}$. The isospin coupling coefficients for the $T=\frac{1}{2}$ states are such that the protons should be in-

involved in the transition more strongly than the neutrons and for the $T=\frac{3}{2}$ states neutrons and protons would be expected to contribute more equally. We suggest that the π^+ enhanced state (or group of states) at 16 MeV contains components of the $T=\frac{1}{2}$ multiplet states.

In summary, the inelastic scattering of π^+ and π^- on ^{13}C yielded a number of striking results. Two transitions were found to be consistent with pure neutron and pure proton excitations. Qualitative arguments were presented to explain these data as transitions to states of principally $2^+ \otimes d_{5/2}$ weak-coupling structure. The weak transitions to the "single-neutron states" at 3.09 and 3.85 MeV were only moderately enhanced in π^- scattering suggesting significant proton particle-hole components in the wave functions or sizable contributions from two-step processes. The excitation of the $[2^+ \otimes p_{1/2}]_{3/2^-, 5/2^-}$ weak-coupling states showed a state dependence of the blocking of the quadrupole strength of the ^{12}C core. Finally, a difference in the structure of π^- and π^+ spectra at about 21 MeV was observed, similar to results⁸ for $^{12}\text{C} + \pi^+$, indicating isospin mixing between $T=\frac{1}{2}$ and $T=\frac{3}{2}$ states. The experimental angular distributions and calculations will be presented in a forthcoming publication.

The authors are indebted to Dr. D. Kurath, Dr. T.-S. H. Lee, Dr. B. F. Bayman, and Dr. P. J. Ellis for helpful discussions. The authors also wish to thank Dr. Lee and Dr. Kurath for permission to quote some of their results prior to publication, and Dr. R. J. Macek for providing the ^{13}C target.

This work was supported in part by the U. S. Department of Energy and the Swiss Institute of Nuclear Physics.

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Static Polarization Effects in the Nucleus-Nucleus Potential

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This letter presents a study of a simple way to relax the frozen-configuration assumption in the calculation of the real part of the nucleus-nucleus potential. The proposed model allows the thickness of the surface layer of each nucleus to vary from the outer side to the interacting side giving rise to polarized shapes which simulate a neck formation. The result is compared to other potentials available in the literature.

The calculation of the nucleus-nucleus potential starting from an energy-density formalism is very convenient when simplifying assumptions about the density of the composite system are made. A common starting point is the frozen-configuration assumption or the sudden approximation¹⁻⁵ according to which the density of the whole system is taken as the sum of the asymptotic individual densities at any separation distance between the interacting nuclei. In practice such a simplification allows one to calculate the interaction potential between any pair of nuclei once the densities are known.

In this Letter I propose a way to relax the frozen-configuration assumption by trying to maintain the simplicity of the calculations. Under mutual influence the nuclei deviate from their spherical shape and I try to describe this polarization effect by a gradual change of the surface layer thickness from an equilibrium value a_0 at the outer side to a value a at the interacting side of each nucleus. This value is found by minimizing the potential with respect to a at each separation distance s_0 between the surfaces, with

$$s_0 = R - R_1 - R_2, \quad (1)$$

where R is the distance between the centers of the nuclei, and R_1 and R_2 are the nuclear radii.

In this way I extend the formalism of Ref. 4 according to which one defines the nucleus-nucleus potential $\tilde{V}(s_0, a)$ as the difference between the binding energy of the composite system at s_0 and the binding energy of the nuclei separated at infinity. The Skyrme-interaction density functional⁶ is used to calculate the binding energies. For the composite system the density is taken as the sum of the individual densities and the kinetic energy densities of the composite system and of the individual nuclei are described by the Thomas-Fermi approximation. The advantage of these approximations is that the Skyrme-interaction energy density H reduces to an algebraic function of the densities ρ_1 and ρ_2 only. Then the potential can be written as the volume integral

$$\tilde{V}(s_0, a) = \int [H(\rho_1^a + \rho_2^a) - H(\rho_1^{a_0}) - H(\rho_2^{a_0})] dv. \quad (2)$$

The parameter a_0 is the equilibrium value of the surface layer thickness for an individual nucleus. As Skyrme-interaction parameters I have chosen the set⁶ SII which gives for a semi-infinite slab $a_0 = 0.48$ fm and $E_{\text{surf}} = 22.38$ MeV/fm² when the Thomas-Fermi approximation is used for the kinetic energy density as defined in Ref. 6. At infinity the densities ρ_1 and ρ_2 are described by

Isospin Mixing of 4^- Particle-Hole States in ^{16}O

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Transitions to $(4^-, T=0)$ states in ^{16}O at 17.79 and 19.80 MeV are found to be strongly asymmetric in π^+ vs π^- inelastic scattering; in contrast, the π^+ and π^- cross sections for the $(4^-, T=1)$ state at 18.99 MeV are equal. Three-state isospin mixing is proposed as an explanation. Off-diagonal charge-dependent mixing matrix elements of -147 ± 25 and -99 ± 17 keV are obtained.

PACS numbers: 21.10.Hw, 25.80.+f

We report the first observation of isospin mixing among three nuclear states which was detected by comparing π^+ and π^- inelastic scattering. This technique has been used to separate proton and neutron components of nuclear excitations at pion energies near the $(3,3)$ resonance,¹ where the ratio of the cross sections for π^+ vs π^- scattering from protons (neutrons) is about 9:1 (1:9). Furthermore, a direct comparison of π^+ and π^- inelastic scattering at these energies from self-conjugate nuclei provides a method of detecting isospin impurities of the excited nuclear states.² In previous cases³⁻⁷ of strong isospin mixing (^8Be , ^{12}C , and ^{16}O), only two states were believed to be involved.

Our study of π^+ and π^- inelastic scattering from ^{16}O at large momentum transfer was carried out on the Energetic Pion Channel and Spectrometer (EPICS) at the Clinton P. Anderson Meson Physics Facility, which has been described in detail elsewhere.⁸ Ice targets of 160 and 320 mg/cm² thickness were used. The incident pion energy was 164 MeV, and the angular range was from 53° to 89° (laboratory). Typical energy resolution was 350 keV full width at half maximum (FWHM). The absolute cross sections were determined by scattering π^+ and π^- from the hydrogen in the ice targets and using the calculated π - p cross sections of Dodder.⁹ The absolute normalization is believed to be accurate to approximately 10% whereas the relative π^+/π^- uncertainty is about 5%.

Spectra obtained from π^+ and π^- scattering at a laboratory angle of 77° are shown in Fig. 1.

The $(4^-, T=0)$ states at 17.79 and 19.80 MeV show large π^+/π^- asymmetries, but the $(4^-, T=1)$ state at 18.98 MeV does not. Yields for these states were obtained by fitting the region between 16 and 23 MeV with a polynomial background and four peaks of fixed line shape, determined by the line shape of the elastic peak for each thickness of target. The relative energies of the three 4^- states were fixed at values obtained in previous studies,^{10,11} while the state at ~ 20.5 MeV was fit when possible (its angular distribution appears to have a minimum near the 4^- maximum and

FIG. 1. Energy loss spectra for π^+ and π^- at an energy of 164 MeV and a laboratory angle of 77°.

may be a 3^- state). From the angular distributions shown in Fig. 2, one may obtain the following ratios of the summed yields for π^+ vs π^- : (1) 17.79 MeV (4^- , $T=0$), $R(\pi^+/\pi^-) = 1.59 \pm 0.12$; (2) 18.98 MeV (4^- , $T=1$), $R(\pi^+/\pi^-) = 0.964 \pm 0.080$; and (3) 19.80 MeV (4^- , $T=0$), $R(\pi^+/\pi^-) = 0.605 \pm 0.049$. (Errors quoted are statistical.) From charge symmetry, these ratios are expected to be unity. For example, the low-lying (3^- , $T=0$) state at 6.13 MeV has a π^+/π^- cross section ratio of 0.98 ± 0.04 at 45° , which is near its maximum.

These states in ^{16}O , which have a $(d_{5/2}, p_{3/2}^{-1})$ configuration, have been seen in one-nucleon transfer reactions¹⁰ and in inelastic proton scattering at medium energies.¹¹ The 18.98-MeV state (4^- , $T=1$) has also been observed in high-energy electron scattering.^{12,13} The excitation energies of these states are well above particle threshold, and because medium-energy pions are strongly absorbed, one may expect π^+/π^- asymmetries to result from differences in proton and neutron single-particle wave functions. These continuum effects in the reaction channels have been investigated by Siciliano and Weiss¹⁴ and cannot explain the asymmetries observed. The authors of Ref. 14 conclude that continuum effects would result in a systematic π^- bias in the cross sections for both $T=0$ and $T=1$ states, rather

than a reversal of the π^+/π^- asymmetry as observed for the $T=0$ states. Our interpretation of the asymmetries for pion excitation of these states is that they are substantially mixed in isospin. In previous cases of two-state isospin mixing,²⁻⁷ the T_- state becomes mostly a proton state (π^+ enhanced) and the T_+ state is predominantly a neutron state (π^- enhanced). For ^{16}O , three 4^- states are known within 2 MeV so that three-state mixing has to be considered. The qualitative picture of the mixing in ^{16}O is that the two $T=0$ states mix through the $T=1$ state with nearly equal magnitudes. The lower state mixes with the middle state, resulting in the lower level becoming mostly a proton state and the middle level becoming mostly a neutron state. However, when the middle state mixes with the upper state, the energy denominator of the mixing changes sign, which results in the state above becoming primarily neutron in composition while the middle state gains in proton strength from this second mixing. Thus, the $T=1$ state retains nearly equal proton and neutron amplitudes, whereas the lower level becomes mostly a proton state and the upper level mostly a neutron state.

If we assume that the charge-dependent part of the nuclear Hamiltonian, H_{cd} , may be treated as a small perturbation, we may write the physical states (labeled $|A'\rangle$, $|B'\rangle$, and $|C'\rangle$) as linear combinations of the unperturbed states of pure isospin (labeled $|A\rangle$, $|B\rangle$, and $|C\rangle$) as

$$\begin{aligned} |A'\rangle &= |A\rangle + \epsilon_1 |B\rangle + \epsilon_3 |C\rangle, \\ |B'\rangle &= -\epsilon_1 |A\rangle + |B\rangle + \epsilon_2 |C\rangle, \\ |C'\rangle &= -\epsilon_3 |A\rangle - \epsilon_2 |B\rangle + |C\rangle, \end{aligned} \quad (1)$$

where $\epsilon_1 = \langle A | H_{cd} | B \rangle / (E_A - E_B)$, $\epsilon_2 = \langle B | H_{cd} | C \rangle / (E_B - E_C)$, and $\epsilon_3 = \langle A | H_{cd} | C \rangle / (E_A - E_C)$. In these calculations we will ignore terms of order ϵ^2 . The unperturbed 4^- states of ^{16}O must be configuration mixed as well because the single-particle, single-hole ($1p-1h$) configurations can result in only two states ($T=0, 1$). Therefore, the unperturbed states are written as

$$\begin{aligned} |A\rangle &= \alpha |1p-1h, T=0\rangle + \sum_i \alpha_i |\psi_i, T=0\rangle, \\ |B\rangle &= \beta |1p-2h, T=1\rangle + \sum_i \beta_i |\psi_i, T=1\rangle, \\ |C\rangle &= \gamma |1p-1h, T=0\rangle + \sum_i \gamma_i |\psi_i, T=0\rangle, \end{aligned} \quad (2)$$

where ψ_i labels possible multiparticle-multihole configurations.

At this point we make the assumption that the distorted-wave impulse approximation (DWIA) provides an adequate description of the pion-nu-

FIG. 2. Center-of-mass differential cross sections for $\pi^\pm$ scattering at 164 MeV.

cleus interaction.¹⁵ This assumption treats the transition operator as a one-body operator on the nuclear space. We note that even from the complicated ground state of ¹⁶O, which contains substantial 2p-2h admixtures,¹⁶ the one-body density matrix elements for 2p-2h to 1p-1h transitions to the "stretched" 4⁺ states are identically zero, for 2p-2h configurations from the $\rho_{1/2}$ shell. Also, contributions of 2p-2h to 3p-3h transitions are dramatically reduced relative to the core to 1p-1h terms. Thus, within the model, only the 1p-1h amplitudes of Eq. (2) are reached.

If we further assume that the energy dependence of the π -nucleon interaction is dominated by the (3,3) channel, the DWIA π -nucleus amplitude for a 1p-1h, unnatural-parity transition from an even-even nucleus may be written as¹⁴

$$\Lambda_{\varphi_z}^T = F[(2 + \varphi_z) + (-1)^T(2 - \varphi_z)], \quad (3)$$

where $\varphi_z = \pm 1$ ($\pi^\pm$) and T ($=0, 1$) is the nuclear isospin. The proton and neutron single-particle wave functions are assumed to be identical, and the differences between π^+ and π^- distorted waves are neglected. The factor F contains all of the details common to the $\pi^\pm$ excitation of the unperturbed states at the same incident pion energy and momentum transfer: distorted waves, radial integrals, angular-momentum recoupling coefficients, etc. Then, to order ϵ_i , the cross sections for $\pi^\pm$ scattering to the isospin mixed states may be written as

$$\begin{aligned} \sigma_{\varphi_z}^{A'} &= |\hat{F}|^2 16 \hat{\alpha} [\hat{\alpha} + 2\hat{\gamma}\epsilon_3 + \varphi_z\epsilon_1], \\ \sigma_{\varphi_z}^{B'} &= |\hat{F}|^2 4 [1 + 4\varphi_z(\hat{\gamma}\epsilon_2 - \hat{\alpha}\epsilon_1)], \\ \sigma_{\varphi_z}^{C'} &= |\hat{F}|^2 16 \hat{\gamma} [\hat{\gamma} - 2\hat{\alpha}\epsilon_3 - \varphi_z\epsilon_2], \end{aligned} \quad (4)$$

where $|\hat{F}|^2(\hat{\alpha}, \hat{\gamma})$ is $|F|^2(\alpha, \gamma)$ multiplied (divided) by β^2 (β) because in the absence of a full DWIA calculation, the absolute magnitude of the 1p-1h strength cannot be determined.

The six summed cross sections for $\pi^\pm$ scattering to the three states were used with the above expressions to solve for the six quantities $\hat{\alpha}$, $\hat{\gamma}$, ϵ_1 , ϵ_2 , ϵ_3 , and $|\hat{F}|^2$. The results of the calculation are shown in Table I. An identical analysis which kept all terms to order ϵ^2 yielded results unchanged from the present work.

The deduced 1p-1h amplitudes for these states are in qualitative agreement with the relative spectroscopic factors obtained by Mairle⁹ in an ¹⁷O(d, t)¹⁶O experiment when the effects of isospin mixing are included, i.e., the 17.79-MeV state has less neutron p-h strength than the 19.80-MeV state, relative to the 18.98-MeV state. The fact that $\hat{\alpha}^2 + \hat{\gamma}^2 \leq 0.54$ indicates further fragmentation of the $T=0$ strength in the excitation spectrum. Because there is no experimental evidence for these other $T=0$ states, we assume that no more than the two observed (4^+ , $T=0$) levels can mix significantly with the (4^- , $T=1$) state. If one assumes that β is unity, as is suggested by the studies of Mairle,¹⁰ and neglects isospin mixing between the 1p-1h and 3p-3h configurations, the 1p-1h $\langle T=0 | H_{cd} | T=1 \rangle$ matrix element obtained is about -240 ± 40 keV. This value is somewhat uncertain, however, because small 3p-3h amplitudes in the $T=1$ state may significantly affect the exact value of the 1p-1h matrix element obtained, as well as the effects of isospin mixing between the 1p-1h and 3p-3h configurations. To determine 1p-1h or 3p-3h matrix elements accurately, it may be necessary to interpret our results within the

TABLE I. Values for the physical and unperturbed energies, configuration-mixing parameters, and the charge-dependent mixing matrix element are shown. Errors on $\hat{\alpha}$, $\hat{\gamma}$, $\langle A | H_{cd} | B \rangle$, $\langle B | H_{cd} | C \rangle$, $\langle A | H_{cd} | C \rangle$, and $|\hat{F}|^2$ are estimates based on the experimental errors. The DWIA parameter $|\hat{F}|^2 = 0.0625 \pm 0.0034$ mb/sr. The values for the unperturbed energies do not include a diagonal charge-dependent energy shift.

Physical energy (MeV)	Unperturbed energy (MeV)	1p-1h amplitudes
17.79 $\pm$ 0.02	17.81 $\pm$ 0.02	$\hat{\alpha} = 0.510 \pm 0.043$
18.98 $\pm$ 0.02	18.98 $\pm$ 0.02	
19.80 $\pm$ 0.02	19.78 $\pm$ 0.02	$\hat{\gamma} = 0.529 \pm 0.046$
Charge-dependent mixing matrix elements		
$\langle A H_{cd} B \rangle = -147 \pm 25$ keV		
$\langle B H_{cd} C \rangle = -99 \pm 17$ keV		
$\langle A H_{cd} C \rangle = 17 \pm 30$ keV		

framework of large-basis shell-model wave functions. Such an analysis is in progress.¹⁷

In conclusion, large asymmetries in π^+ vs π^- excitations of 4^- states in ^{16}O are interpreted as evidence of substantial isospin mixing among the states. Off-diagonal charge-dependent matrix elements of -147 ± 25 and -99 ± 17 keV are obtained when the data are analyzed with a simple model for three-state mixing. Before definite conclusions can be reached concerning the magnitude of charge-dependent forces in nuclei more experimental and theoretical study is needed; however, intermediate-energy pions will be a useful tool in the study of this aspect of nuclear structure.

This work was supported in part by the U. S. Department of Energy, by the Robert A. Welch Foundation, and by the Swiss Institute for Nuclear Research.

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Identification of $\Delta S = 1$ Transitions in ^{13}C by Measurement of Pion Inelastic Excitation Functions

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(Received 17 February 1981)

Differential cross sections for $^{13}\text{C}(\pi, \pi')$ were measured between 100 and 300 MeV for momentum transfers of $1.1\hbar\text{ fm}^{-1}$ and $1.4\hbar\text{ fm}^{-1}$. In this energy range the different energy dependences of the spin-dependent and spin-independent parts of the pion-nucleon interaction provide a very sensitive method of discriminating between transitions that proceed with a spin transfer ($\Delta S = 1$) or without a spin transfer ($\Delta S = 0$). Five transitions in ^{13}C were found to be dominated by the $\Delta S = 1$ transition density amplitude.

PACS numbers: 25.80.+f, 27.20.+n

The work of Moore *et al.*¹ indicated that new information can be obtained from the measurement of inelastic pion excitation functions. In this Letter we report on the use of excitation functions of inelastic pion scattering to distinguish between $\Delta S = 0$ and $\Delta S = 1$ transitions, where ΔS is the spin transfer to the target nucleus. Differential cross sections for two transitions in ^{13}C , known to proceed predominantly by $\Delta S = 0$, were found to have energy dependences very different from that of a recently determined^{2,3} pure $\Delta S = 1$, pure neutron particle-hole excitation of a stretched state. Four other transitions were found to be dominated by $\Delta S = 1$. Such an effect was also seen in the work of Cottingham *et al.*⁴ in which natural and unnatural parity transitions in $^{12}\text{C}(\pi, \pi')$ had dramatically different energy dependences. The explanation⁵ of these different energy dependences is based on two facts. Firstly, at energies near the $[3, 3]$ resonance the spin-dependent and spin-

independent parts of the pion-nucleus scattering amplitude have quite different energy dependences for a given momentum transfer. Secondly, transitions that involve a spin transfer, $\Delta S = 1$, to the target can be caused only by the spin-dependent part of the force and transitions without a spin transfer, $\Delta S = 0$, are predominantly due to the spin-independent part of the force.

The pion-nucleon scattering amplitude can be written in the following form if the interaction is dominated by the $[3, 3]$ resonance,⁶

$$f(k, k') = \alpha(k)(2 \cos \theta + i \vec{\sigma} \cdot \hat{n} \sin \theta),$$

where k (k') is the pion momentum before (after) the collision, θ is the scattering angle in the pion-nucleon center-of-mass frame, $\vec{\sigma}$ is the spin operator for the nucleon, and $\hat{n}$ is the normal to the scattering plane. The coefficient $\alpha(k)$ is given in terms of the pion-nucleon phase shift δ by $\alpha(k) = k^{-1} \exp(i\delta) \sin \delta$. Only the operator $\vec{\sigma} \cdot \hat{n}$ can

lead to a spin transfer ($\Delta S = 1$). Siciliano and Walker have shown that a similar expression holds for pion-nucleus scattering.⁵ At a momentum transfer $q \approx q_0$, i.e., near the maximum of the differential cross section $\sigma(\theta)$ for pion-nucleus scattering,

$$\sigma(\theta) = \Gamma(E)[4M^2(q_0)\cos^2(\theta) + S^2(q_0)\sin^2(\theta)],$$

if we assume dominance of the $[3, 3]$ resonance, the validity of the fixed-scatterer impulse approximation and a one-step reaction mechanism. Here E is the pion energy and θ is the scattering angle in the pion-nucleus laboratory frame. Both the spin-independent form factor $M(q_0)$ and the spin-dependent form factor $S(q_0)$ contribute to natural parity transitions, but these transitions are usually dominated by $M(q_0)$. Only $S(q_0)$ can contribute to $\Delta S = 1$ transitions (if Fermi motion corrections are neglected). $\Gamma(E)$ contains the energy dependence of the pion-nucleon amplitudes, of the distortions, and the phase-space factors.⁵

At a constant momentum transfer q , the scattering angle θ is a simple function of the incident energy or wave number k , $\theta = 2\sin^{-1}(q/2k)$. For example, to keep the momentum transfer constant at a q value near the maximum in the angular distribution for a $\Delta L = 2$ transition in ^{13}C , the scattering angle must be decreased from about 72° at $T_\pi = 100$ MeV to about 32° at $T_\pi = 300$ MeV. (Because of its large width the $[3, 3]$ resonance is dominant over this whole energy range.) Thus the energy dependence of $\sigma(\theta)$ for $\Delta S = 1$ transitions and $\Delta S = 0$ transitions measured at constant momentum transfer will be very different simply because of the difference between the $\sin^2\theta$ and $\cos^2\theta$ functions. The energy dependences of the $\sin^2\theta$ and $\cos^2\theta$ functions are expected to dominate the shapes of the excitation functions since $\Gamma(E)$ depends only relatively weakly on the energy for constant q . Consequently, the cross sections for $\Delta S = 1$ transitions should decrease with increasing energy since $\sin^2\theta$ decreases between 100 MeV ($\theta \approx 72^\circ$) and 300 MeV ($\theta \approx 32^\circ$). In contrast, the cross sections for $\Delta S = 0$ transitions should increase with increasing energy due to the associated $\cos^2\theta$ dependence.

We have measured excitation functions for inelastic scattering of pions from ^{13}C at incident energies between 100 and 300 MeV using the EPICS spectrometer at the Clinton P. Anderson Meson Physics Facility (LAMPF). The target was a 15 cm $\times$ 23 cm sheet of carbon, of areal density 210 mg/cm², enriched in ^{13}C to 99% and

covered on both sides by thin (≈ 1 mg/cm²) Kapton foils. The energy resolution width was about 250 keV [full width at half maximum (FWHM)] (see Ref. 2 for typical pion spectra). At each energy the scattering angles were chosen to keep the momentum transfer fixed at either $1.1\hbar\text{ fm}^{-1}$ or $1.4\hbar\text{ fm}^{-1}$. The former value is close to the first maximum in the angular distribution for a $\Delta L = 2$ transition and the latter is close to the maximum in the angular distribution for the strongly π^- -enhanced transition to a state at 9.5 MeV.² At the smaller momentum transfer only π^+ data were taken; at the larger momentum transfer both π^+ and π^- data were taken and only the excitation function having the best statistics for each state (either π^+ or π^-) is presented here. To determine the overall normalization of the absolute cross sections, yields were measured for $\pi^+ + p$ as a function of energy at $\theta_{\text{lab}} = 40^\circ$ and compared with cross sections calculated with use of the pion-nucleon phase shifts of Rowe, Saloman, and Landau.⁷ The error in the normalization is estimated as $\pm 10\%$.⁸ This error is not included in the error bars of the figures which represent only the statistical and the fitting errors.

The (π^+, π^-) cross sections for the transitions to the strongly excited $\frac{3}{2}^-$ state (3.68 MeV) and the unresolved $\frac{5}{2}^-$, $\frac{7}{2}^+$ doublet (7.5 MeV) were measured at $q = 1.1\hbar\text{ fm}^{-1}$ and found to increase uniformly with energy (Fig. 1). The $\frac{3}{2}^-$ and $\frac{5}{2}^-$ states are collectively enhanced and predicted to be dominated by the $\Delta L = 2$, $\Delta S = 0$ transition amplitude.⁹ At $q = 1.1\hbar\text{ fm}^{-1}$ the cross section measured for the doublet at 7.5 MeV is expected to be due mostly to the $\frac{5}{2}^-$ state and thus the excitation function for this group should show the features of a $\Delta S = 0$ transition, like the excitation function for the transition to the $\frac{3}{2}^-$ state. Indeed, for both states the simple $\cos^2\theta$ relation (Fig. 1, solid lines) predicts the trend of the data quite well. A distorted-wave impulse approximation (DWIA) calculation of the $\frac{3}{2}^-$ state with use of the code DWPI of Eisenstein and Miller¹⁰ with an "energy-shifted" optical potential¹¹ and a simple collective form factor reproduces the shape of the excitation function in detail (Fig. 1, broken line). The relatively small differences between the $\cos^2\theta$ function and the DWIA result verify the claims made above regarding the weakness of the energy dependence of Γ .

The (π^-, π^+) excitation function for the transition to the 9.5-MeV state was measured at $q = 1.4\hbar\text{ fm}^{-1}$ and found to decrease uniformly with energy (Fig. 2), in sharp contrast to the data for

FIG. 1. Excitation functions for $^{13}\text{C}(\pi^+, \pi^{+'})^{13}\text{C}^*$ to the $\frac{3}{2}^-$ (3.68 MeV) and $\frac{5}{2}^-$ (7.55 MeV) states measured at $q = 1.1 \hbar \text{ fm}^{-1}$. The solid lines are the $\cos^2\theta$ dependences arbitrarily normalized to the data at 220 MeV. The dashed line is the result of a DWIA calculation for the $\frac{3}{2}^-$ state.

the $\Delta S=0$ transitions discussed above. The energy dependence is very well accounted for by $\sin^2\theta$ (solid line).

It has been proposed that this state is the $\frac{9}{2}^+$ member of a weak-coupling multiplet¹² based on a $1d_{5/2}$ neutron coupled to the first excited 2^+ state in ^{12}C . In this model the large π^- asymmetry, $A = [\sigma(\pi^-) - \sigma(\pi^+)] / [\sigma(\pi^-) + \sigma(\pi^+)] = 0.8 \pm 0.2$, can be explained as due to a pure neutron $1p_{3/2} \rightarrow 1d_{5/2}$ particle-hole excitation.² The shell-model calculations of Millener and Kurath¹³ predict a $\frac{9}{2}^+$ state at 9.5 MeV which has a very large overlap with the weak-coupling state. The DWIA calculations of Lee and Kurath³ with use of the Millener-Kurath wave functions reproduce not only the π^- enhancement very well but also the absolute cross sections⁸ for exciting this state to within about 20%. According to this model, the $\frac{9}{2}^+$ state is reached solely by an unnatural parity transition with a total-angular-momentum transfer $\Delta J = 4$, an orbital-angular-momentum transfer $\Delta L = 3$, and a spin transfer $\Delta S = 1$. The experimental excitation function for this state from the present work is characteristic of a $\Delta S = 1$ transition, in excellent agreement with the shell-model calculation.^{3, 13}

We remark that the enhancement of $\Delta S = 1$ tran-

FIG. 2. Excitation functions for $^{13}\text{C}(\pi^\pm, \pi^{\pm'})^{13}\text{C}^*$ to states at 9.5 and 21.60 MeV (with π^-), and at 16.05, 17.92, and 21.37 MeV (with π^+), measured at $q = 1.4 \hbar \text{ fm}^{-1}$. The solid lines are simple $\sin^2\theta$ dependences.

sitions relative to $\Delta S=0$ transitions at low pion energies (≈ 100 MeV) is of considerable help in searches for weak unnatural parity transitions. At or above resonance (> 180 MeV) such transitions may be barely visible against a background of strong $\Delta S=0$ transitions.

Four states, or groups of states, in the excitation energy region from 12 to 24 MeV were found to be strongly excited at large momentum transfer. Their angular distributions are fairly structureless and peak at large angles characteristic of a large angular-momentum transfer to high-spin states.⁸ The centroids of these groups are at 16.05, 17.92, 21.37, and 21.60 MeV. Their excitation functions measured at $q = 1.4 \hbar \text{ fm}^{-1}$ are very similar to that of the $\frac{9}{2}^+$ state at 9.5 MeV and they are also very well described by $\sin^2\theta$ (Fig. 2). Thus the transitions to these states must be dominated by $\Delta S = 1$. The 16.05-MeV

state is π^+ enhanced, $A = -0.6 \pm 0.2$ (Ref. 2), in agreement with the shell-model prediction^{3,13} for a $\frac{9}{2}^+$ state close to 16 MeV. The complex close to 21.5-MeV peaks at 21.37 MeV in π^+ scattering and at 21.60 MeV in π^- scattering. The state or group of states at 17.92 MeV is excited about equally by both π^+ and π^- . An interpretation of these results in terms of shell-model predictions is difficult because of the large number of states involved. The 21.5-MeV complex probably contains several $\frac{7}{2}^+$ and $\frac{9}{2}^+$ states. Furthermore, the $T = \frac{1}{2}$ and $T = \frac{3}{2}$ states at these energies are most likely mixed in isospin. Isospin mixing was not included in Ref. 13 but its importance is suggested by the similarity of the pion spectra² close to 21.5 MeV in ^{13}C with those close to 19 MeV in ^{12}C (Ref. 14).

The 180° electron scattering data of Hicks *et al.*¹⁵ and Dubach *et al.*¹⁶ are in agreement with our $\Delta S = 1$ assignments for some of these transitions. They found $M4$ transitions to states at 9.49, 16.06, and 21.43 MeV but did not see any significant strength at ≈ 17.9 MeV. A comparison of the different excitation strengths from $(\pi^+, \pi^{+'})$, $(\pi^-, \pi^{-'})$, and (e, e') allows conclusions about the isospin transfer ΔT since the transverse (e, e') form factor is dominated by $\Delta T = 1$. The near equality of $\sigma(\pi^-)$ and $\sigma(\pi^+)$ for the group at 17.92 MeV suggests a pure isospin transfer of either $\Delta T = 0$ or $\Delta T = 1$, but the lack of any significant $M4$ strength from (e, e') strongly supports a pure $\Delta T = 0$ transition. The excitation energy of one of the strong $M4$ transitions from (e, e') , $E_x = 21.43 \pm 0.03$ MeV,¹⁶ is close to the centroid of the peak seen in $(\pi^+, \pi^{+'})$. This suggests a concentration of the $\Delta T = 1$ strength in the lower-energy part of the 21.5-MeV complex.

In summary, these data have demonstrated the utility of measurements of excitation functions of inelastic pion scattering in the identification of $\Delta S = 1$ transitions. This technique has been used to confirm that the pure transition to the $\frac{9}{2}^+$ state at 9.5 MeV involves $\Delta S = 1$ and to identify four $\Delta S = 1$ transitions to states in the region from 12 to 24 MeV in ^{13}C . It is anticipated that this tech-

nique can be used to separate the $\Delta S = 0$ and $\Delta S = 1$ components of mixed transitions. This will allow stringent tests of shell-model predictions.

The authors are indebted to Dr. E. R. Siciliano, Dr. G. E. Walker, Dr. M. A. Franey, and Dr. T.-S. H. Lee for helpful discussions and to Dr. R. L. Boudrie, Dr. G. Kyle, Dr. J. Piffaretti, and Dr. H. A. Thiessen for assistance in the early stages of data taking. The authors would also like to thank Dr. R. J. Macek for providing the ^{13}C target.

This work was supported in part by the U. S. Department of Energy.

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Strong Cancellations of Neutron and Proton Transition Amplitudes Observed in Pion Inelastic Scattering from ^{14}C

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Differential cross sections were measured for inelastic scattering of 164-MeV π^+ and π^- from ^{14}C . Large cross-section ratios, $R = \sigma(\pi^+)/\sigma(\pi^-)$ (or R^{-1}), were observed, two being significantly larger than the free π -nucleon value. Lower limits are $R > 26$, $R^{-1} > 17$, and $R > 11$ for states at 8.32 MeV (2^+), 11.67 MeV (4^-), and 17.26 MeV (4^-), respectively. These values are interpreted as being due to strong cancellations of the neutron and proton components of the transition amplitudes.

PACS numbers: 25.80.+f, 21.10.Hw

At energies near the (3, 3) π -N (pion-nucleon) resonance, the ratio, $R = \sigma(\pi^+)/\sigma(\pi^-)$, of the cross sections for π^+ and π^- scattering from free protons (neutrons) is about 9 ($\frac{1}{9}$). Thus, comparisons of π^+ and π^- inelastic scattering from nuclei should provide a sensitive method of separating the proton and neutron components of inelastic transitions. Cross-section ratios near the free π -N values are expected for pure proton or pure neutron particle-hole (p-h) excitations if the impulse approximation is valid. However, in previous studies on even- A , $N > Z$ nuclei, such as ^{18}O (Ref. 1) and ^{28}Mg (Ref. 2), values of R (or R^{-1}) in the range of 1.0 to 2.0 were found. These small values have been attributed to the large amount of core excitation present in these nuclei. Deviations from $R=1$ for $N=Z$ nuclei, which arise from charge symmetry violation (e.g., due to the Coulomb force), have been observed and interpreted successfully as due to transitions to

an isospin-mixed doublet in ^{12}C (Ref. 3) and a triplet in ^{16}O (Ref. 4). The free π -neutron value of $R^{-1} \approx 9$ was detected⁵ so far only for a transition in the odd- A nucleus ^{13}C and was interpreted as the result of a pure neutron p-h transition to a "stretched" state.

In this Letter, we report on the first observation of ratios R significantly larger than 9 in a measurement of inelastic pion scattering on ^{14}C at an incident energy $T_\pi = 164$ MeV. The large differences in π^+ and π^- cross sections are seen to provide unusually transparent signatures of the shell-model structure of the transitions. As discussed in detail below, the near vanishing of either π^+ or π^- cross sections (but not both) for a specific state comes about from the strong cancellation of the proton and neutron transition amplitudes.

The experiment was performed at the Clinton P. Anderson Meson Physics Facility with the

FIG. 1. Energy loss spectra for π^+ and π^- scattering from ^{14}C at $\theta_{\text{lab}} = 42^\circ$ and $T_\pi = 164$ MeV.

energetic pion channel and spectrometer which has been described in detail elsewhere.⁶ The target consisted of ~ 9 g of carbon powder enriched to 83% in ^{14}C . The $^{14}\text{C}/^{12}\text{C}$ atom ratio was 4.87 ± 0.24 .⁷ The carbon powder was pressed to a thickness of ~ 0.10 g/cm² into six target cells, each consisting of a U-shaped stainless-steel frame covered with 0.025-mm-thick windows made of stainless steel. Since the ^{14}C target was smaller than the beam spot size, strips of natural graphite were placed above and below the ^{14}C target cells in order to obtain ^{12}C and ^{14}C spectra simultaneously. Additional spectra were taken from stainless-steel foils as target. These spectra enabled us to derive "clean" spectra via a channel-by-channel subtraction, shown in Figs. 1 and 2. The energy resolution obtained was about 200 keV (full width at half maximum).

Cross sections at 42° and 66° for selected states are presented in Table I. The ^{14}C cross sections were normalized with use of the π^+ cross sections for the 4.44-MeV state in ^{12}C , the ^{12}C (4.44 MeV) yield from the ^{14}C target, and the known $^{14}\text{C}/^{12}\text{C}$ atom ratio. We employed this method of normalization since it does not rely on the assumption

FIG. 2. Same as Fig. 1, but at 66° .

of uniform target thickness. The absolute normalization was obtained by comparing π^+ -hydrogen yields with the π -proton cross sections of Dodder.⁸ The ^{12}C cross sections (Table I), which were measured using the graphite strips, are in good agreement with previous work.⁹

The most surprising feature of the present data is the sharp contrast between the near equality of $\sigma(\pi^+)$ and $\sigma(\pi^-)$ for the 2_1^+ state at 7.01 MeV and the highly asymmetric cross sections for the 2_2^+ state at 8.32 MeV. At $\theta_{\text{lab}} = 42^\circ$, which is near the first maximum of known $\Delta J = 2$ angular distributions, no π^- yield could be detected above background (Fig. 1). The experimental cross sections and errors (Table I) yield a lower limit of $R > 26$ for the 2_2^+ state. This is dramatically larger than the free π -proton value of 9.

Similarly, at $\theta_{\text{lab}} = 66^\circ$ (Fig. 2), a state at 11.67 MeV is observed only in (π^-, π^-') and a state at 17.26 MeV is seen essentially only in (π^+, π^+') . The lower limits for the cross-section ratios are $R^{-1} > 17$ and $R > 11$, respectively. Angular distributions for these states (not shown) have maxima near 66° and shapes similar to those of previously measured $\Delta J = 4$ transitions in ^{12}C (Ref. 3), ^{13}C (Ref. 5), and ^{16}O (Ref. 4), all of which are due to excitations of the "stretched" ($d_{5/2}, p_{3/2}^{-1}$)

TABLE I. The measured π^+ and π^- differential cross sections (lab), ^a cross-section ratios R , and asymmetries A ^b for states in ^{14}C and the 4.44-MeV state in ^{12}C .

Target	E_x (MeV)	J^π	θ_{lab} (deg)	$d\sigma/d\Omega_{\pi^+}$ (mb/sr)	$d\sigma/d\Omega_{\pi^-}$ (mb/sr)	R	A
^{14}C	7.01	2^+	42°	1.01 ± 0.08	0.90 ± 0.07	1.12 ± 0.07	-0.06 ± 0.03
^{14}C	8.32	2^+	42°	0.14 ± 0.01	$< 0.0054^c$	$> 26^c$	$-0.99^{+0.09}_{-0.01}$
^{14}C	11.67^d	(4^-)	66°	$< 0.0028^c$	0.049 ± 0.005	$< 1/17^c$	$0.96^{+0.04}_{-0.10}$
^{14}C	17.26^d	(4^-)	66°	0.094 ± 0.008	0.005 ± 0.003	$> 11^c$	-0.89 ± 0.06
^{12}C	4.44	2^+	42°	2.85 ± 0.17	2.88 ± 0.18	0.99 ± 0.06	0.006 ± 0.03

^aThe errors quoted are based on an estimate of all known uncertainties but do not include a $\pm 20\%$ error in the overall normalization. In calculating R and A , the cancellation of some errors which are common to π^+ and π^- was taken into account.

^b $A \equiv [\sigma(\pi^-) - \sigma(\pi^+)] / [\sigma(\pi^-) + \sigma(\pi^+)]$.

^cAt the 90% confidence level.

^dThe estimated uncertainty in the energies of these states is ± 0.1 MeV.

p-h configuration. On the basis of this similarity to previous pion data, we suggest a J^π assignment of 4^- for these states.

It has been known for some time that the p -shell model¹⁰ predicts only one low-lying 2^+ state, yet the two experimental 2^+ states at 7.01 and 8.32 MeV share the p -shell strength for transfer reactions,¹¹ electromagnetic transitions,¹¹ and the (π^-, γ) reaction.¹² On the basis of previous work^{13,14} a reasonable approximation to the wave functions of the two 2^+ states ($i=1, 2$) is

$$|^{14}\text{C}; 2_i^+, T=1\rangle \\ = \alpha_i |(p^{-2p})_{2+}\rangle + \beta_i |(p^{-4})_{0+}(sd^{2n})_{2+}\rangle,$$

with $\alpha_1 = \alpha_2 = 1/\sqrt{2}$ and $\beta_1 = -\beta_2 = -1/\sqrt{2}$, and for the ground state (g.s.)

$$|^{14}\text{C}; 0_1^+, T=1\rangle \\ = \alpha_0 |(p^{-2p})_{0+}\rangle + \beta_0 |(p^{-4})_{0+}(sd^{2n})_{0+}\rangle.$$

The relative phases of the p -shell (proton) and s - d -shell (neutron) parts of the 2^+ states indicate constructive interference of the proton and neutron components in the transition from the g.s. to the 2_1^+ state and destructive interference for the 2_2^+ state. This destructive interference could result in a near vanishing of $\sigma(\pi^-, 2_2^+)$ even if β_0 is relatively small because of the enhancement of the neutron part of the transition amplitude in π^- scattering.

To prove this point quantitatively, we performed momentum-space distorted-wave impulse-approximation¹⁵ calculations. The p-h matrix elements for the p -shell proton holes and the s - d -shell

neutron particles were obtained from the work of Ellis and Engeland¹⁶ and the coefficient α_0 [$\beta_0 = -(1 - \alpha_0^2)^{1/2}$] was taken as an adjustable parameter. Harmonic-oscillator radial wave functions were used for the bound states of the active nucleons with an oscillator parameter $b=1.7$ fm for both protons and neutrons.¹³ Both spin transfer values of $\Delta S=0$ and $\Delta S=1$ were included in calculating the scattering amplitudes. To account for the truncation of the model space, effective charges for both protons and neutrons were used to enhance the $\Delta S=0$ piece of the nuclear transition matrix elements.¹⁵ The polarization charges for the protons and neutrons were set equal ($\delta_p = \delta_n$) and treated as a second adjustable parameter. Further details of the calculation will be presented in a subsequent publication.

With $\delta_p = \delta_n = 0.4$, $\alpha_0 = 0.81$, and $\beta_0 = -0.19$, the calculations yield (in mb/sr at 42°) $\sigma(\pi^+, 2_1^+) = 1.04$, $\sigma(\pi^-, 2_1^+) = 0.80$, $\sigma(\pi^+, 2_2^+) = 0.21$, and $\sigma(\pi^-, 2_2^+) = 0.008$. The data indicate an even more complete cancellation for the 2_2^+ than these calculations do. Possible reasons for the remaining discrepancies are presently being investigated. Nevertheless, the basic features of the data are correctly described as due to an interference of the neutron and proton parts of the transition amplitude.

The data for the two proposed 4^- states at 11.67 and 17.26 MeV are also suggestive of cancellation effects. In any simple model, several $4^-, T=1$ states are expected with large components of the "stretched" ($d_{5/2}, p_{3/2}^{-1}$) configuration. The 4^- state lowest in energy should have a large

overlap with a state formed by a $d_{5/2}$ neutron coupled to a $\frac{3}{2}^-$, $T=\frac{1}{2}$ ^{13}C core.¹³ This state would be reached mainly by a neutron p-h excitation from a $T=\frac{1}{2}$ core component in the ground state of ^{14}C . The experimental ratio for the 4_1^- state at 11.67 MeV, $R^{-1} > 17$, is larger than the free π -neutron value of $R^{-1} \approx 9$, indicating the presence of small contributions from proton p-h excitations to the transition density amplitude with a sign opposite to the one of the principal neutron p-h excitation.

Although the lower limit of $R > 11$ for the other prominent 4^- state at 17.26 MeV is essentially consistent with a pure proton excitation ($R \approx 9$), such an interpretation is unlikely since it would imply a transition to a state strongly mixed in isospin. Cross-section ratios estimated from a shell-model calculation by Kurath¹⁷ for 4^- model states at 12.7 and 16.9 MeV are in good agreement with our data, although the estimated absolute cross sections are about a factor of 2 too large. A complete comparison of all the data with these predictions will be presented in a forthcoming publication.

In summary, our measurements on ^{14}C have shown for the first time that π^+/π^- cross-section ratios for nuclear excitations can be considerably larger than the value of 9 for scattering from free nucleons at the (3, 3) resonance. In addition, candidates for the first 4^- states of "stretched" ($d_{5/2}, p_{3/2}^{-1}$) configuration in ^{14}C have been located. We have interpreted the extraordinarily large π^+/π^- ratios as being due to cancellations of the neutron and proton components of the transition amplitudes. The direct manifestation of such cancellation phenomena in a simple comparison of the measured π^+ and π^- spectra demonstrates the

value of pion scattering for elucidating the structure of nuclear states.

Discussions with P. J. Ellis, H. T. Fortune, M. A. Franey, D. Kurath, and C. Fred Moore are gratefully acknowledged. The authors also thank D. Kurath for making his calculations for the negative-parity states available to us prior to the experiment.

This work was supported in part by the U. S. Department of Energy and the Robert A. Welch Foundation.

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Measurement of Isospin Mixing in ^4He and Its Implications for Charge-Symmetry Breaking

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(Received 10 April 1985)

π - ^4He inelastic cross sections have been measured at $T_\pi = 180$ MeV. In the region of the $J^\pi = 1^-$ states ($E_x \approx 23$ to 30 MeV) the π^+/π^- cross-section ratio R_π was found to be 1.05 ± 0.08 at $\theta_{\text{lab}} = 30^\circ$. Such a small deviation from 1.0 implies that isospin mixing between the $T=0$ and $T=1$ states in ^4He is quite weak, in striking contrast to the strong isospin mixing deduced from the large ratio of photonucleon cross sections, $R_\gamma = \sigma(\gamma, p)/\sigma(\gamma, n) \approx 1.7$. Thus the conclusion drawn from the photonucleon work, that there is a large charge-symmetry-breaking nuclear force in ^4He , needs to be reexamined.

PACS numbers: 25.80.Fm, 25.10.+s, 27.10.+h

A recent critical review¹ of the numerous measurements² of the (γ, p) and (γ, n) photonucleon cross sections on ^4He presents a cross-section ratio $R_\gamma \equiv \sigma(\gamma, p)/\sigma(\gamma, n)$ between 1.5 and 1.9 at excitation energies E_x below 30 MeV. Measurements of the cross sections for the proton³ and neutron⁴ capture reactions, $^3\text{H}(p, \gamma)$ and $^3\text{He}(n, \gamma)$, confirm the (γ, p) and (γ, n) results. The experimental value of $R_\gamma \sim 1.7$ is in striking contrast to the value of 1.0 which would be expected if the proton-proton and neutron-neutron forces were equal so that the excited states of ^4He would be states of good isospin T . The γ radiation in the photonucleon reactions involves predominantly electric dipole radiation ($E1$). Thus the large value of R_γ may be due to isospin mixing between the $J^\pi = 1^-$, $T=0$, and $T=1$ states in ^4He (Ref. 1). Because Coulomb effects can cause R_γ to be only slightly larger ($\approx 10\%$) than 1.0 at 2 to 3 MeV above the $p + ^3\text{H}$ threshold (19.82 MeV),⁵⁻⁷ the authors of Ref. 1 suggested the presence of a large

charge-symmetry-breaking (CSB) nuclear force in ^4He which would cause strong isospin mixing between the 1^- states. An analysis¹ of the photonucleon data with the two-level isospin-mixing formula of Barker and Mann⁸ yielded a CSB matrix element $\langle T=1 | H_{\text{CSB}} | T=0 \rangle$ of nearly 500 keV, i.e., much larger than the value expected from the Coulomb force (≈ 100 to 150 keV). An even larger matrix element (≈ 2.5 MeV) was extracted⁹ in a calculation which included $3\hbar\omega$ excitations. The existence of large CSB forces such as invoked in Refs. 1 and 9 would fundamentally change our present understanding of the nuclear force.

It has been shown^{10,11} that CSB forces of the magnitude required to reproduce the experimental value of R_γ generate large differences between the polarization (P) and the analyzing power (A) in the reaction $^3\text{H}(p, n)^3\text{He}$. Experimentally,^{12,13} however, only small differences have been observed between A and P , in very good agreement with theoretical predictions¹¹ which include only the Coulomb interaction as a CSB

force. It is therefore necessary to measure the degree of isospin mixing by another method.

Inelastic scattering of π^+ and π^- near the $[3,3]$ resonance has been established^{14,15} to be a reliable method for the determination of isospin mixing. For the $J^\pi = 1^+$ isospin doublet in ^{12}C (12.71 MeV, $T=0$, and 15.11 MeV, $T=1$) the CSB matrix element has been found¹⁴ to be ≈ 150 keV. This result agrees very well with electromagnetic measurements and theoretical expectations for isospin mixing due to the Coulomb force. Thus, in order to obtain an independent determination of isospin mixing in ^4He , we have measured differential cross sections $\sigma(\pi^+)$ and $\sigma(\pi^-)$ for inelastic pion scattering from ^4He at $T_\pi = 180$ MeV.

The energetic pion channel and spectrometer system (EPICS)¹⁶ at the Los Alamos Meson Physics Facility (LAMPF) was used to measure spectra at $\theta_{\text{lab}} = 20^\circ$, 30° , and 40° up to $E_x = 45$ MeV excitation energy. The target was helium gas, cooled to a temperature $T \approx 17$ K at a pressure $P \approx 2$ atm. The target container was a cylinder of 0.23-m height and 0.127-m diameter with nickel walls of 40-mg/cm² areal density. The areal density of the cooled helium was ≈ 65 mg/cm². The energy resolution was ≈ 500 keV (FWHM) and the angular acceptance was 3° .

The absolute differential cross sections were determined by a measurement of π -hydrogen yields, with methane as a target, and normalizing the yields to $\pi + p$ cross sections, calculated from the phase shifts of Thiessen and Sobottka.¹⁷ We also measured spectra from the empty target container to determine the background contribution from the target can. For $\theta_{\text{lab}} = 30^\circ$ the background amounted to about 15% of the total counts.

The experimental spectra at $\theta_{\text{lab}} = 30^\circ$ (after background subtraction) were converted to differential cross sections $\sigma(\pi) \equiv d^2\sigma/d\Omega dE$. The results are shown in Fig. 1 for $E_x \leq 36$ MeV. The error bars are due to statistics and the uncertainties in background subtraction only. Uncertainties in target thicknesses, pion decay fractions, wire-chamber efficiencies, computer live time, spectrometer acceptance, beam monitoring, and predicted $\pi + p$ cross sections lead to a conservative estimate of $\pm 15\%$ uncertainty in the absolute differential cross sections.

In contrast to the photonucleon reactions, which are dominated by electric dipole absorption, inelastic scattering by pions excites all the states in ^4He , except for the $J^\pi = 0^-$ state. All excited states of ^4He are particle unbound. Thus the spectra show a broad continuum of states above threshold (≈ 20 MeV). Nevertheless, the first excited 0^+ state at 20.5 MeV and the 2^- state near 22 MeV are clearly visible in Fig. 1. As indicated by the theoretical curves (to be discussed below), the 1^- continuum peaks near 25 MeV. At

FIG. 1. Spectra of $^4\text{He}(\pi^+, \pi^+')$ and $^4\text{He}(\pi^-, \pi^-')$ at $\theta_{\text{lab}} = 30^\circ$ and $T_\pi = 180$ MeV. The curves are the results of distorted-wave impulse-approximation (DWIA) calculations as described in the text. The DWIA curves for the 2^- states have been multiplied by a factor of 1.35 for both π^+ and π^- in order to fit the data better.

$E_x > 31$ MeV, the 2^+ continuum makes the largest contribution to the cross sections.

Our principal result is contained in Fig. 2 which shows near unity values for the cross-section ratio $R_\pi = \sigma(\pi^+)/\sigma(\pi^-)$ at all E_x beyond the threshold region ($E_x \geq 22$ MeV). Only the (E_x -dependent) statistical and background subtraction errors are shown for R_π which was averaged over 400-keV intervals. Several sources of absolute cross-section uncertainty, such as target thicknesses and spectrometer acceptance, do not contribute to the uncertainty in R_π . The other sources of (mostly E_x -independent) error contribute a systematic uncertainty of $\pm 8\%$. Averaged over the region of the 1^- states ($E_x = 23$ to 30 MeV), where $R_\gamma = 1.7 \pm 0.2$, we find $R_\pi = 1.05 \pm 0.08$ at $\theta_{\text{lab}} = 30^\circ$. The error of ± 0.08 is dominated by the systematic uncertainty in R_π . Values of R_π near

FIG. 2. R_π as a function of excitation energy E_x at $\theta_{lab} = 30^\circ$ and $T_\pi = 180$ MeV. Solid line: DWIA prediction.

threshold are larger than 1.0 because the separation threshold for protons (19.82 MeV) is lower than that for neutrons (20.58 MeV). At 20° and 40° the values of R_π in the region of the 1^- states are also consistent with 1.0. At 20° the background was larger than at the other angles which made a realistic estimate of the error too difficult. At 40° the 2^- states are more strongly excited than at 30° where the differential cross sections for the 1^- states are expected to peak. Thus the data at 30° provide the most precise determination of R_π in the region of the 1^- states.

In Ref. 1 the large value of R_γ was attributed to isospin mixing between $T=0$ and $T=1$, $J^\pi=1^-$ states. Application of the two-state mixing formalism of Ref. 8 led to a ratio of the $T=0$ reaction amplitude (a_0) to the $T=1$ amplitude (a_1) of $|a_0/a_1|=0.13$ for the transition to an isospin-mixed state near 25 MeV, which was presumed to be predominantly a $T=1$ state. Within the two-level mixing model this value of $|a_0/a_1|$ represents a $T=0$ admixture in the $T=1$ state of amplitude $|\beta|=0.13$. Such a large admixture should be easily detectable in inelastic pion scattering because of the isospin dependence of the pion-nucleon interaction.

At pion energies near the $[3,3]$ resonance the pion-nucleon interaction enhances the $T=0$ parts of the transition density amplitudes over the $T=1$ parts by a factor of $+2$ for π^- and a factor of -2 for π^+ . Thus in the plane-wave Born approximation the cross-section ratio would be $R_\pi = [(\alpha - 2\beta)/(\alpha + 2\beta)]^2 = 2.9$ for a $T=1$ state with a $T=0$ admixture of amplitude $\beta = -0.13$, where $\alpha = (1 - \beta^2)^{1/2}$. The observed value of R_π shows that isospin mixing is much smaller, i.e., β is of the order of 1% if the two-level mixing formalism describes this case.

As pointed out in Refs. 1 and 9, the $T=0$, $S=0$,

1^- state in a $1\hbar\omega$ model space is entirely due to spurious center-of-mass motion. Shell-model calculations generate higher-order nonspurious $T=0$, $S=0$ states but mixing with the $T=1$ states is much more complicated than in two-level^{8,9} mixing of isolated states. Since the ^4He states are all very broad and overlap, isospin mixing changes continuously with E_x as do the contributions from $S=1$ states. For equal spectroscopic amplitudes the $S=1$ contributions to the cross sections are smaller than the $S=0$ contributions because of the relatively weaker π -nucleon spin-orbit interaction. However, they are not negligible as for photonucleon reactions.

The conclusion of small isospin mixing in ^4He is fully supported by distorted-wave calculations using the wave functions from the recoil-corrected continuum shell model (RCCSM).¹⁸ The Coulomb force is the only CSB force applied in the RCCSM calculations and the resulting wave functions provide very good agreement with low-energy nucleon scattering data. These include differential cross sections ($d\sigma/d\Omega$) and A for elastic scattering of neutrons from ^3He and protons from ^3H , as well as $d\sigma/d\Omega$, A , and P for the reaction $^3\text{H}(p,n)^3\text{He}$.^{12,13} They also reproduce the $^4\text{He}(\gamma,p)$ absolute cross section and the shapes of the angular distributions for the capture reactions $^3\text{He}(n,\gamma)$ and $^3\text{H}(p,\gamma)$.¹⁹⁻²¹ However, they predict $R_\gamma \approx 1.0$. We note that, by imposing continuum boundary conditions on the excited nucleons, the RCCSM reaction calculations include the quasielastic process as well as the scattering through resonance states.

The procedure followed to calculate the pion differential cross sections $d^2\sigma/d\Omega dE_x$ by the distorted-wave impulse approximation has been discussed by Halderson *et al.*²² The transition densities were calculated with a modified version of ALLWORLD²³ and entered into the program MSUDWPI²⁴ to generate the $d^2\sigma/d\Omega dE_x$ for E_x between 20 and 35 MeV. For the distorted waves we employed the wave equation of Stricker, McManus, and Carr.²⁵ The optical potential parameters were determined from the free π -nucleon phase shifts evaluated 20 MeV below the incident pion energy in the spirit of Cottingham and Holtkamp.²⁶ The nuclear density was of Gaussian form, $\exp(-r^2/a^2)$, with $a = 1.3$ fm. The DWIA cross sections were found to be quite sensitive to the distorting potentials. However, the predicted cross-section ratio R_π above 23 MeV is always near 1.0, ranging from about 1.0 to 1.1.

The theoretical predictions for the cross sections shown in Fig. 1 were obtained with an energy-dependent optical potential in the outgoing channel. They are presented for the individual multipolarities (0^+ , 2^- , 1^- , 2^+) as well as for the sum (solid line). The π^+ and π^- predictions for the 2^- states were renormalized by a factor of 1.35 as suggested by the data.

For the other states the curves shown are the predicted cross sections without a renormalization.

In conclusion, cross sections measured for inelastic pion scattering from ^4He show only small π^+/π^- asymmetries. The absolute differential cross sections are reproduced very well by predictions using the RCCSM wave functions. The RCCSM has been very successful in fitting a large body of data for the mass-4 system. The only data for which the RCCSM seems to fail are the absolute cross sections for $^4\text{He}(\gamma, n)$ and thus the ratio R_γ below $E_x = 35$ MeV. Even without as thorough a theoretical treatment as the RCCSM provides, the pion scattering casts considerable doubt on the interpretation of the experimental value of R_γ in terms of isospin mixing due to a large CSB force. Our data show only a very small amount of isospin mixing between the excited states of ^4He .

The authors are indebted to Dr. R. L. Boudrie, Dr. P. J. Ellis, Dr. M. A. Franey, and Dr. E. R. Siciliano for helpful discussions and to Mr. M. K. Jones for his help with the figures. This work was supported in part by the U.S. Department of Energy, the Japan Society for Promotion of Science, the U.S.-Japan Cooperative Science Program of the National Science Foundation, and the Robert A. Welch Foundation.

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Test of the Δ -Hole Model through the Energy Dependence of $(\pi, \pi'\gamma)$ Angular Correlations on ^{12}C

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(Received 5 August 1986)

For the reaction $^{12}\text{C}(\pi, \pi')^{12}\text{C}^*(2^+, 4.44 \text{ MeV})$, $^{12}\text{C}^* \rightarrow ^{12}\text{C}(\text{g.s.}) + \gamma$, pion- γ angular correlations have been measured in and out of the reaction plane. The data taken at a pion momentum transfer of $q = 0.47 \text{ fm}^{-1}$ for incident kinetic energies of 116, 140, 162, 180, and 226 MeV confirm Δ -hole model predictions, in which the Δ propagation in the nucleus is explicitly taken into account.

PACS numbers: 25.80.Fm, 14.20.Gk, 27.20.+n

One of the most challenging goals of modern nuclear physics is to understand the role of excited nucleons in a nucleus. In this context the $\Delta(3,3)$ resonance as the lowest excited state of the nucleon with strangeness zero is of special interest. Its behavior in the nuclear medium can be studied most suitably by pion-nucleus scattering in the region of incident energies between about 100 and 300 MeV. Theoretically these medium effects are adequately considered in the so-called isobar-doorway models by the explicit introduction of isobar-hole intermediate states and an elaborate treatment of their propagation.¹⁻⁴ The Δ -hole model derived from this concept^{5,6} together with calculations in the static limit are the theoretical basis for the discussion of the data presented here.

In the Δ -hole calculations starting from the optical-model expansion of the multiple-scattering formalism, medium corrections are taken into account by treating some properties of the Δ resonance which are different from those of the free Δ : the reduced phase space available to the nucleon in the decay of the Δ in the presence of other nucleons (Pauli blocking), binding effects, and true pion absorption in nonmesonic channels ($\Delta N \rightarrow NN$). In the static limit the same calculations are performed with neglect of these medium corrections and the Δ propagation.⁶ Their results can be considered as a reference point for the dynamical phenomena to be investigated.

In inelastic pion scattering reactions to discrete final states of a nucleus the Δ -hole model often yields a

description of the differential cross sections nearly equivalent to that from calculations in the static limit. For these reactions the consideration of the magnetic-substate population of the excited state is of particular interest. On the one hand the transition amplitudes for the different magnetic substates are expected to be more sensitive to medium effects than the more inclusive differential cross section; on the other hand, symmetry considerations within the Δ -hole model show that different excitation mechanisms populate the individual substates differently. Therefore, observables sensitive to the magnetic-substate populations are particularly suited to test the validity of the Δ -hole model.

Pion-gamma angular-correlation data are sensitive to the magnetic-substate population of pion scattering to a discrete final state with subsequent gamma decay. A first $(\pi, \pi'\gamma)$ experiment in the Δ -resonance region has been performed at the Swiss Institute of Nuclear Research (SIN) at an incident pion energy of 162 MeV on the 2^+ (4.44 MeV) state in ^{12}C .⁷ In this experiment no energy resolution was available for the scattered pions, and the angular-correlation data were taken only in the reaction plane at a single incident energy. Already from these rather modest data there were indications that the Δ -nucleus dynamics was important for the description of the pion-nucleus interaction.

In this Letter we report on a new $(\pi, \pi'\gamma)$ angular correlation experiment with considerably improved accuracy and range. The angular correlations were mea-

sured in and out of the reaction plane at different incident energies covering the region of the $\Delta(3,3)$ resonance. The experiment was performed in the π M1 area at SIN. The nuclear state studied was again the $2^+(4.44 \text{ MeV})$ state in ^{12}C . The positive pions scattered from a graphite target with an area density of about 1.70 g/cm^2 were detected with the SUSI spectrometer facility⁸ in coincidence with the deexcitation gamma rays of ^{12}C . The gamma rays were detected by six movable NaI detectors, three of them placed in the reaction plane and three of them at 45° below the reaction plane. The data discussed here were taken at a pion momentum transfer of $q = 0.47 \text{ fm}^{-1}$ for incident kinetic energies of 116, 140, 162, 180, and 226 MeV. To demonstrate the quality of our data, Fig. 1 shows a spectrum of the scattered pions coincident with the 4.44-MeV deexcitation gamma rays of ^{12}C compared to the spectrum without the coincidence requirement, which is totally dominated by the peak of elastically

FIG. 1. Spectrum of pions with an incident kinetic energy of 162 MeV scattered from ^{12}C at a momentum transfer of $q = 0.47 \text{ fm}^{-1}$. Upper part: without coincidence requirement. Lower part: in coincidence with the 4.44-MeV gamma rays detected in one of the NaI detectors.

scattered pions. Although, as a result of random coincidences, the peak of elastically scattered pions is not completely suppressed in the coincident spectra, the inelastic events obtained from these spectra are practically free of background. A detailed description of the experimental setup together with the appropriate test procedures and monitoring systems, data analysis, and discussion of possible systematic errors will be published in a forthcoming paper.⁹

To present our data we use the angular-correlation function defined as

$$W = 4\pi (d^2\sigma/d\Omega_\pi d\Omega_\gamma) (d\sigma/d\Omega_\pi)^{-1}. \quad (1)$$

The determination of the differential cross section $d\sigma/d\Omega_\pi$ requires the determination of the yield N_{in} of inelastically scattered pions.⁹ For the double-differential cross section $d^2\sigma/d\Omega_\pi d\Omega_\gamma$ the yield N_{coi} of coincident events has to be measured. If both yields are measured simultaneously, the angular-correlation function W can be derived from the simple relation

$$W = 4\pi N_{coi}/N_{in}\epsilon_\gamma d\Omega_\gamma, \quad (2)$$

where experimental uncertainties associated with the pion spectrometer as well as the dependence on target thickness and pion flux cancel out. The remaining product $\epsilon_\gamma d\Omega_\gamma$ of efficiency and solid angle of the NaI detectors has been determined in a separate experiment.¹⁰ This new approach of determining the angular-correlation function W itself, rather than the double-differential cross section $d^2\sigma/d\Omega_\pi d\Omega_\gamma$, as has been done so far,^{7,11} results in the considerably improved accuracy of the data.

Choosing the quantization axis perpendicular to the reaction plane and regarding the reaction as a $0^+ \rightarrow 2^+ \rightarrow 0^+$ transition, we can parametrize the angular-correlation function W_{in} for measurements in the reaction plane as

$$W_{in}(\theta_\gamma = 90^\circ, \phi_\gamma) = A + C \sin^2(\phi_\gamma - \phi_2). \quad (3)$$

For the out-of-plane geometry the angular correlation function W_{out} is then given by

$$W_{out}(\theta_\gamma = 45^\circ, \phi_\gamma) = A' + C' \sin^2(\phi_\gamma - \phi_2) + D \sin^2(\phi_\gamma - \phi_0), \quad (4)$$

with $A' = \frac{1}{8}(15 - 6A - 4C - 4D)$ and $C' = \frac{1}{4}C$.

The five independent parameters A , C , D , ϕ_2 , and ϕ_0 can be determined from the present experiment. They are functions of the transition amplitudes to the different magnetic substates with $m = -2, 0, +2$ of the $2^+(4.44 \text{ MeV})$ state in ^{12}C . The amplitudes for $m = \pm 1$ are zero according to Bohr's theorem.¹² The angular-correlation functions were calculated in the

framework of the Δ -hole model and the static limit, with use of exactly the same methods and input parameters as described in Ref. 6. These calculations exhibit characteristic differences between the two approaches, particularly in their energy dependence in the region of the first minimum of the differential cross section, which corresponds to the momentum transfer of $q = 0.47 \text{ fm}^{-1}$ chosen in our experiment. These characteristic differences, which clearly influence the pattern of the angular-correlation function, motivated us to study the energy dependence of the angular-correlation functions.

Our results are shown in Fig. 2. The solid curves are

FIG. 2. In-plane and out-of-plane angular-correlation function W for the reaction $^{12}\text{C}(\pi, \pi'\gamma)$ at a momentum transfer of $q = 0.47 \text{ fm}^{-1}$ for different incident kinetic energies. The solid curves are best fits according to Eqs. (3) and (4). The dashed and dot-dashed curves represent predictions of the Δ -hole model and the static limit, respectively.

best fits to the data points according to Eqs. (3) and (4). Their good agreement with the experimental points confirms the reliability of the present data. The dashed and dot-dashed curves are the predictions of the Δ -hole model and the static limit, respectively. The finite solid angles of the detectors are taken into account by a suitable averaging of the calculations.⁹ Obviously, in the Δ -hole model the amplitude of W_{in} decreases significantly with increasing energy, whereas the amplitude of W_{out} remains nearly constant. The correlation-function amplitudes in the static limit are consistently smaller and nearly energy independent. The experimental data follow the predictions of the Δ -hole model. The difference between the two models depends sensitively on the nonlocality of the transition operator, expected to play an important role at small q , and on the distortion effects.⁶ We find that both of these effects are about equally important for understanding the discrepancies between the Δ -hole and the static calculations, shown in Fig. 2. In any case, our data show that medium effects become more important in the region below resonance. To get more insight about this fact we plan to measure pion-gamma angular correlations as a function of the pion scattering angle.

In conclusion, we have shown that the Δ -nucleus dynamics as included in the Δ -hole model is needed to describe the presented $(\pi, \pi'\gamma)$ angular-correlation data, especially in their energy dependence. Calculations in a static limit ignoring the propagation of the intermediate Δ resonance cannot reproduce the experimental data. There is, however, a convincingly good agreement with the predictions of the Δ -hole model.

One of us (D.D.) is greatly indebted to the kind hospitality extended to him at SIN, where part of the work was completed. This work has been supported by the German Bundesministerium für Forschung und Technologie.

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$^{12}\text{C}(\pi^\pm, \pi^\pm'p)^{11}\text{B}$ Reaction near the Giant Dipole RegionSung Hoon Yoo, A. Williams, S. Mordechai,^(a) and C. Fred Moore*University of Texas at Austin, Austin, Texas 78712-1081*

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Cross sections for the $^{12}\text{C}(\pi^\pm, \pi^\pm'p)^{11}\text{B}$ reaction have been measured and compared with the results of distorted-wave impulse-approximation calculations that employ the factorization approximation for quasifree scattering. Near the giant dipole resonance of ^{12}C the calculations underestimate the cross sections for $(\pi^-, \pi^-'p)$. The angular distributions for $(\pi^+, \pi^+'p)$ and $(\pi^-, \pi^-'p)$ are different and indicate that in this region there is interference between direct decay and semidirect decay.

PACS numbers: 25.80.Fm, 24.30.Cz, 27.20.+n

The response of the continuum of nuclear states above nucleon breakup threshold to inelastic scattering has been the subject of intensive research.¹ Transitions to the giant resonances (GR's) can proceed in competition with the quasielastic scattering process. Thus, a detailed understanding of the reaction mechanism is needed in order to unravel the structure of the continuum. For example, the extent to which isospin is a good quantum number for the giant resonances is of great importance in the study of nuclear structure.² We believe that coincidence measurements between inelastically scattered probes and emitted secondary particles provide a powerful tool for these investigations. The isospin selectivity of π^+ and π^- scattering makes pion probes particularly useful in a study of the continuum.

Coincidence experiments involving pions as a probe can be divided into two groups: experiments in the region where quasielastic scattering dominates [$E_x(\text{target}) \geq 40$ MeV and backward angles]³⁻⁷ and experiments in the region of the giant resonances [$E_x(\text{target}) \leq 40$ MeV and forward angles].^{8,9} Indeed, Chant, Rees, and Roos¹⁰ have shown that quasifree single-nucleon knockout calculations, carried out with the code THREEDEL¹¹ are in good agreement with the measured $^{12}\text{C}(\pi^+, \pi^+'p)^{11}\text{B}(\text{g.s.})$ cross sections of Ziocck *et al.*⁴ at large momentum transfer and high $E_x(^{12}\text{C})$. These calculations use a factorized form of the distorted-wave impulse approximation (DWIA), and include optical-model distortions of the incoming pion, outgoing pion, and final-state proton. The processes that contribute to the lower $E_x(\text{target})$ of the continuum, however, are more complicated. It has been suggested^{9,12} that, in this GR

region, direct decay (due to quasifree-knockout scattering) and semidirect decay (due to resonant inelastic scattering to states of good isospin) compete with each other in a coherent way.

The current study is aimed at the excitation region near the giant dipole resonance (GDR) of ^{12}C . In this Letter, we compare cross sections for the $^{12}\text{C}(\pi^\pm, \pi^\pm'p)$ reaction with DWIA calculations performed with the code THREEDEL in order to evaluate the importance of quasifree-knockout scattering in the excitation-energy region near the GDR. We also present values for the ratio $R = \sigma(\pi^+, \pi^+'p)/\sigma(\pi^-, \pi^-'p)$, which may provide information on the isospin structure of the continuum.

The experiment was performed on the Energetic Pion Channel and Spectrometer (EPICS)¹³ at Los Alamos National Laboratory. Scattered pions were detected in the focal plane of the high-resolution EPICS spectrometer. Protons were detected in coincidence with the scattered pions using five plastic-BGO (bismuth-germanate) "phoswich" detectors mounted in the vacuum scattering chamber. Measurements were made at an incident pion energy of 180 MeV. The target was a carbon foil of natural isotopic composition and of areal density 91 mg/cm² mounted at 60° with respect to the beam direction. The energy loss in the detector entrance foil and in the target limited the minimum detectable proton energy to about 4 MeV (at the center of the target). The pion scattering angle θ_{lab} was chosen to be 20°, near the maximum in the angular distribution for the GDR in ^{12}C .¹⁴ Protons were detected at laboratory scattering angles $\theta_{\text{lab}} = -120^\circ, -90^\circ, -60^\circ, 60^\circ, \text{ and } 90^\circ$ with respect to the incident beam. A relative measure of the pion beam

intensity was provided by a toroidal pickoff upstream of the pion production target which measured the primary proton beam current. Typical average pion fluxes were $\approx 2.8 \times 10^7/\text{sec}$ for π^+ and $1.5 \times 10^7/\text{sec}$ for π^- . The data were normalized by comparing yields measured for π^+ and π^- scattering from hydrogen (using a CH_2 target of areal density 73 mg/cm^2) to cross sections calculated using the π - N phase shifts of Rowe, Salomon, and Landau.¹⁵ The energy resolution in the (π, π') and $(\pi, \pi'p)$ reactions is about 200 keV and 4 MeV, respectively.

Missing-mass spectra for π^+ and π^- scattering are shown in Fig. 1. Singles spectra for π^+ (red) and π^- (blue) are presented in the upper portion. The π^+ and π^- cross sections are nearly equal everywhere as expected for a self-conjugate nucleus because of charge symmetry except for a known isospin-mixed doublet near 19 MeV.¹⁶

Figure 1(b) shows the pion missing-mass spectrum, gated by the requirement of detecting a coincident proton at an energy which implies that the excitation energy of the residual nucleus, ^{11}B , is less than 10 MeV, and summed over all proton detectors. In contrast to the singles spectra, the $(\pi, \pi'p)$ coincidence yields are larger for π^+ than π^- throughout the spectrum. The missing-mass spectrum gated by detecting a proton leading to excited states of ^{11}B higher than 10 MeV is plotted in Fig.

1(c). In this case, which includes multiparticle breakup states, the (π^+, π^+p) and (π^-, π^-p) cross sections are about the same at all energies. The 4-MeV threshold for proton detection in our phoswich detectors seems to have a minimal effect on the results of our coincidence data, since we are considering the decay of $^{12}\text{C}^*$ states above $E_x = 20 \text{ MeV}$.

The inequality of the (π^-, π^-p) and (π^+, π^+p) cross sections for $E_x(^{11}\text{B}) < 10 \text{ MeV}$ can be qualitatively understood by simple arguments. If the reaction process is quasifree knockout, we expect a ratio R close to 9 as for π^+ and π^- scattering from free protons. Nearly as large a ratio is obtained from the factorized DWIA calculations performed with the code THREEDEE. The curves plotted in Fig. 1(b) correspond to scattering from a proton bound in the $1p$ shell. A spectroscopic factor $C^2S = 3.98$, the summed $1p$ -shell spectroscopic factor predicted by Cohen and Kurath,¹⁷ and a separation energy $S_p = 15.8 \text{ MeV}$ were assumed. The calculations in Fig. 1(c) are for scattering from a $1s$ -shell proton with $C^2S = 2.0$, the value of the shell-model limit, and $S_p = 34.3 \text{ MeV}$. Both sets of calculations show π^+ scattering to be larger than π^- by nearly the free π - p ratio (for example, we calculate $R \sim 7.36$ for $1p$ knockout near the GDR). However, the experimental ratio is only 1.59 on the average (Table I).

Both the shape and magnitude of the (π^+, π^+p) spectrum gated by $E_x(^{11}\text{B}) < 10 \text{ MeV}$ are well described by the DWIA. However, the (π^-, π^-p) data for the same gate are much larger than the predicted values [Fig. 1(b)]. This discrepancy would be larger if we had used the $1p$ -shell spectroscopic factor of 2.9 and $1s$ -shell spectroscopic factor of 1.8 reported in Ref. 10. For the data from $E_x(^{11}\text{B}) > 10 \text{ MeV}$ gate, the agreement between experiment and the DWIA prediction is poor for both π^+ and π^- scattering [Fig. 1(c)].

The angular distributions of the emitted protons are plotted in Fig. 2 as a function of the outgoing proton angle in the center-of-mass system of the recoil ^{12}C . The cross section for events leading to the ground state or the low-excitation states of ^{11}B , i.e., $E_x(^{11}\text{B}) < 10 \text{ MeV}$, summed over $E_x(^{12}\text{C})$ from 20 to 30 MeV, is shown in

FIG. 1. Missing-mass spectra: blue for π^- and red for π^+ . (a) $^{12}\text{C}(\pi^\pm, \pi^\pm)^{12}\text{C}^*$ singles spectra at $\theta_\pi = 20^\circ$ and $T_\pi = 180 \text{ MeV}$. (b) $^{12}\text{C}(\pi^\pm, \pi^\pm p)^{11}\text{B}$ coincidence spectra, gated by $E_x(^{11}\text{B}) < 10 \text{ MeV}$. Red (blue) solid curve is a DWIA calculation of π^+ (π^-) $1p$ -shell knockout. (c) $^{12}\text{C}(\pi^\pm, \pi^\pm p)^{11}\text{B}$ reaction, gated by $E_x(^{11}\text{B}) \geq 10 \text{ MeV}$. Red (blue) solid curve is a DWIA calculation of π^+ (π^-) $1s$ -shell knockout.

TABLE I. The ratios $R = \sigma(\pi^+, \pi^+p) / \sigma(\pi^-, \pi^-p)$ at each proton detector and the ratio of summed cross section. The $\sigma(\pi^\pm, \pi^\pm p)$ data were obtained by summing cross sections from 20 to 30 MeV in $E_x(^{12}\text{C})$ with the $E_x(^{11}\text{B}) < 10 \text{ MeV}$ gate, at $T_\pi = 180 \text{ MeV}$ and $\theta_{\text{lab}} = 20^\circ$.

$\theta_{\text{p.c.m.}}$	R (DWIA)	R (Experiment)
-60.3°	8.59	1.99 ± 0.41
-28.5°	7.89	3.09 ± 0.62
3.9°	6.75	2.50 ± 0.61
127.3°	5.29	0.47 ± 0.12
155.5°	6.02	0.33 ± 0.11
R of summed σ	7.36	1.59 ± 0.16

FIG. 2. Angular distribution in the center-of-mass system of the recoil $^{12}\text{C}^*$. (a) The missing-mass spectra were summed over $E_x(^{12}\text{C}) = 20$ to 30 MeV and $E_x(^{11}\text{B}) < 10$ MeV. Red (blue) solid curve is a DWIA calculation of π^+ (π^-) 1p-shell knockout. (b) The missing-mass spectra were summed over $E_x(^{12}\text{C}) = 41$ to 70 MeV and $E_x(^{11}\text{B}) \geq 10$ MeV. Red (blue) solid curve is a DWIA calculation of π^+ (π^-) 1s-shell knockout calculations.

Fig. 2(a). In Fig. 2(b) data for the higher-excitation states of ^{11}B , $E_x(^{11}\text{B}) \geq 10$ MeV, were summed over $E_x(^{12}\text{C})$ from 41 to 70 MeV. The curves are the DWIA calculations described earlier. The (π^+, π^+p) data with the $E_x(^{11}\text{B}) < 10$ MeV gate are reasonably well described by the DWIA. However, the (π^-, π^-p) data exhibit no clear peak in the recoil direction in contradiction to the DWIA. In Table I we present the ratio R of the data leading to $E_x(^{11}\text{B}) < 10$ MeV and the DWIA predictions for 1p-shell knockout summed from 20 to 30 MeV of $E_x(^{12}\text{C})$. The experimental value of R varies from a maximum of $R = 3.09 \pm 0.62$ near the quasifree-knockout direction to a minimum of $R = 0.33 \pm 0.11$ in the opposite direction. However, the calculations give $R = 8$ and 6 at these two angles, respectively.

The calculations discussed so far include only the quasifree-knockout process. Another process that can contribute to this $(\pi^\pm, \pi^\pm p)$ reaction in the GR region is a semidirect one where the pion excites a state of ^{12}C in the GR region that subsequently decays through emission of a proton. If the state in ^{12}C has good isospin and if the difference between the neutron and proton penetrabilities is neglected, R must be equal to 1 at all emitted proton angles. In this case the decay of the state is

governed by branching ratios and these are independent of the manner in which the state was created. Furthermore, the angular distribution should be symmetric about 90° . The data for $20 \leq E_x(^{12}\text{C}) \leq 30$ MeV with the $E_x(^{11}\text{B}) < 10$ MeV gate could be qualitatively explained by a mixture of these two processes: direct (due to quasifree knockout) and semidirect (due to inelastic scattering to states of good isospin). The angular distributions of the decay proton indicate that the (π^+, π^+p) is dominated by the direct decay whereas, at least, the (π^-, π^-p) must have a strong contribution from the semidirect process. This process must, of course, also contribute to (π^+, π^+p) , although the good agreement between absolute experimental cross sections and THREEDEE predictions suggests a predominance of the quasifree process. We propose that the observed strong angle dependence of R is probably due to an interference between the amplitudes for these two processes.

In order to describe a situation which lies between the limits of quasifree knockout and the excitation and decay of states of good isospin, one may use a form of the doorway model.¹⁸ In this model, the interaction of the pion probe with the nucleus leads to proton particle-hole and neutron particle-hole states in the continuum with amplitudes approximately in the ratio of the free pion-nucleon couplings. These continuum states couple either to the GR states with width Γ_R , or they decay directly into a potential scattering state with width Γ_D (the quasifree process). The decay of the GR states would lead to equal amplitudes for proton and neutron emission, i.e., $R = 1$, but the interference with the quasifree process causes π^+/π^- asymmetries. The enhancement of the proton decay observed in the current (π^-, π^-p) data above the DWIA calculations indicates that Γ_R and Γ_D must be comparable in size for the continuum near the GR region of ^{12}C . This interference would be less important for (π^+, π^+p) because the direct amplitude is 3 times larger than for (π^-, π^-p) . Therefore, the decay of the continuum in the region of the GR is largely governed by how it was excited. The absolute cross sections predicted by THREEDEE depend on the choice of spectroscopic factors, but not on the ratio R . Thus, we base our conclusion on the failure of simple DWIA calculations to reproduce R . We have made no attempt to include higher-order effects in the π -nucleus scattering such as those which have been predicted to arise from the Δ -hole model.⁷

These observations in the region of the GDR in ^{12}C can be contrasted with the result obtained at higher excitations energies in ^{12}C [Figs. 1(c) and 2(b)]. In this high-excitation region, $40 \leq E_x(^{12}\text{C}) \leq 70$ MeV, we find that more than half of the cross section seen in the coincidence spectrum corresponds to the data leading to $E_x(^{11}\text{B}) \geq 10$ MeV. For these events we observe a broad bump in Fig. 1(c) centered near 55 MeV of excitation in ^{12}C . The angular distribution of protons associated with this bump also appears to peak near the recoil

direction but the ratio R [Fig. 2(b)] is near unity at all angles. The DWIA calculations for $1s$ -shell knockout do not resemble these data at all. The near equality of the (π^+, π^+p) and (π^-, π^-p) cross sections suggests that protons and neutrons are involved equally in the reaction. However, we do not believe that, for $E_x(^{12}\text{C}) \geq 40$ MeV, states of good isospin would play a major role except for possible double resonances.¹⁹ It is also possible that direct two-, three-, and four-nucleon removal are important here. Lourie *et al.*²⁰ also observed considerable strength in this region of $E_x(^{12}\text{C})$ in the $^{12}\text{C}(e, e'p)$ reaction. They interpreted this strength as due to multinucleon reaction mechanisms. The failure of the one-nucleon-knockout calculations with THREEDEE to reproduce the magnitude and the near equality of the π^+ and π^- data suggests the importance of one of these processes for $(\pi, \pi'p)$.

In summary, we have measured cross sections for the $^{12}\text{C}(\pi^\pm, \pi^\pm p)$ reactions, and have compared the results with the factorized DWIA calculations. Neither the DWIA calculations, which assume a quasifree-knockout process, nor the assumption that the reaction is dominated by states of good isospin in ^{12}C (the GDR) can explain the data. This leads to the speculation that inelastic scattering to the giant dipole region in ^{12}C contains two components, one of which is direct (quasifree), the other being semidirect (resonance). The ratio R shows an angular dependence that indicates coherent interference between these amplitudes.

The authors thank Professor N. Chant and Professor Phil Roos for sending us the code THREEDEE and for useful discussions and Dr. Richard Silbar for helpful conversations. This work was supported in part by the U.S. Department of Energy, the Robert A. Welch Foundation, and the U.S.-Israel Binational Science Foundation.

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Asymmetry Measurement of Pion Elastic Scattering from Polarized ^{13}C in the Energy Region of the P_{33} Resonance

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Analyzing powers A_y were measured for π^+ and π^- elastic scattering from polarized ^{13}C at energies near the P_{33} resonance. At $T_\pi=132$ MeV the values of A_y are significantly different from zero for π^- . For π^+ at 132 MeV and for both π^- and π^+ at all other energies, the A_y are mostly consistent with zero. These data differ from the predictions of present pion-nucleus reaction theories, especially at large momentum transfers.

PACS numbers: 25.80.Dj, 24.70.+s

Since significant nuclear polarizations can now be achieved by the dynamic nuclear-polarization (DNP) technique,¹ it has become possible to measure the left-right asymmetries or analyzing powers A_y in pion scattering from nuclear targets.²⁻⁴ Measurements of A_y allow sensitive tests of π -nucleus interaction models^{2,5,6} which include medium modifications of the free pion-nucleon interaction in nuclei. In addition, such measurements contain information on the isoscalar spin-flip strength of nuclear transitions which is difficult to obtain otherwise.

A recent experiment at the Paul Scherrer Institute (PSI) by Tacik *et al.*⁴ and Meier *et al.*⁷ on $^{15}\text{N}(\pi^+, \pi^+)$ at $T_\pi=164$ MeV revealed unexpectedly small asymmetries in sharp contrast to the large A_y predicted by theory. In this Letter we report A_y measurements on polarized ^{13}C . Angular distributions of A_y and of differential cross sections $d\sigma(\theta)/d\Omega$ were measured for both π^- and π^+ at one energy below (132 MeV) and one above (about 230 MeV) the P_{33} resonance. At $T_\pi=132$ MeV, the A_y of π^- scattering were found to be nonzero

near the angular regions corresponding to the first and the second minima of the differential cross sections. A survey was also made at several energies (114-180 MeV) across the resonance for π^- scattering to search for predicted large A_y at momentum transfers (q) near the second minimum of $d\sigma(\theta)/d\Omega$, but A_y consistent with zero were found.

The scattering amplitude of pion scattering from a spin- $\frac{1}{2}$ nucleus can be expressed as

$$t = f(\theta) + ig(\theta)\hat{n} \cdot \sigma, \quad (1)$$

where σ is the nuclear Pauli spin matrix, $\hat{n} = (\mathbf{k} \times \mathbf{k}')/|\mathbf{k} \times \mathbf{k}'|$ with $\mathbf{k}$ and $\mathbf{k}'$ being the momenta of the incoming and outgoing pions, and $f(\theta)$ and $g(\theta)$ are, respectively, the spin-independent and spin-dependent pion-nucleus scattering amplitudes. The former proceeds without a spin transfer ($\Delta S=0$) to the nucleus; the latter involves a spin transfer ($\Delta S=1$). $d\sigma(\theta)/d\Omega$ for pion elastic scattering from nuclei with nonzero spin is dominated by the spin-independent amplitude. A contribution from the smaller spin-dependent amplitude is usually difficult

to observe since $d\sigma(\theta)/d\Omega = |f(\theta)|^2 + |g(\theta)|^2$. However, the left-right asymmetry, defined as

$$A_y = \frac{(d\sigma/d\Omega)_\uparrow - (d\sigma/d\Omega)_\downarrow}{(d\sigma/d\Omega)_\uparrow + (d\sigma/d\Omega)_\downarrow} = \frac{2\text{Im}[f(\theta)g(\theta)^*]}{|f(\theta)|^2 + |g(\theta)|^2} \quad (2)$$

involves the interference of $f(\theta)$ and $g(\theta)$, and is therefore sensitive to the spin-dependent scattering amplitude.

Pion elastic scattering is more sensitive to the isoscalar than the isovector part of the interaction. Thus, our data complement measurements of the (isovector-dominated) magnetic form factor obtained from electron scattering. By measuring both π^+ and π^- scattering, we also obtain information on the isovector terms. As mentioned above, asymmetry data should provide tests of models of the pion-nucleus interaction. Indeed, inclusion of second-order terms in the theoretical calculations^{2,5,6} provides larger changes in the predicted A_y than in $d\sigma(\theta)/d\Omega$.

The experiment was carried out at the Clinton P. Anderson Meson Physics Facility (LAMPF). The material of the polarized target was 99% ^{13}C -enriched 1-butanol ($^{13}\text{C}_4\text{H}_{10}\text{O}$) in the form of frozen beads of about 1 mm in diameter. The beads were contained in a cylindrical Teflon cell immersed in a liquid- ^3He bath inside a copper microwave cavity. The temperature of the target was kept below 0.5 K. The target was polarized either up or down with respect to the reaction plane by ^{1-3}DNP in a magnetic field of 2.5 T. Polarizations of ^{13}C and ^1H were measured by a nuclear-magnetic-resonance system. The polarizations were calibrated by measuring the thermal equilibrium³ signals periodically. The average polarization of ^{13}C was about 28%. A thin ^{13}C slab target was used to collect additional differential-cross-section data.

The left-right asymmetries were obtained by detecting the pions scattered from the polarized target with opposite spin orientations at the same scattering angles. The outgoing pions were detected by the Large Acceptance Spectrometer.^{8,9} The angular acceptance of 8° was divided into two 4° angular bins for the angular-distribution data (Fig. 2) and into three 2.7° angular bins for the energy-dependence data (Fig. 3). The energy resolution was 2–3 MeV (FWHM) (Fig. 1), limited primarily by target thickness and inhomogeneity. Contributions from the unresolved 3.09-MeV peak are expected to be very small¹⁰ even at the minima of the elastic cross sections. The tails from the unresolved 3.68/3.85-MeV doublet make only small contributions in the region of the elastic peak.

In terms of measurable quantities, the asymmetry of pion scattering from polarized ^{13}C ($J = \frac{1}{2}$) is

$$A_y = \frac{N_\uparrow - N_\downarrow}{(N_\uparrow - B)P_\uparrow + (N_\downarrow - B)P_\downarrow} = \frac{\text{DIFF}}{\text{SUM}} \quad (3)$$

Here $P_\uparrow$ and $P_\downarrow$ are the transverse polarizations of the ^{13}C target with spin orientation parallel (spin up) and

antiparallel (spin down) to $\hat{n}$. $N_\uparrow$ and $N_\downarrow$ are the corresponding scattering yields. The background B in the region of the elastic peak originated from the target container (copper microwave cavity and Teflon cell) and from the oxygen in the butanol. A two-step subtraction was made (Fig. 1) using data from a replica of the cryogenic target but without the butanol and ^3He , and data from this replica filled with H_2O .

We extracted A_y by first generating spectra of A_y [Eq. (3)] and its uncertainty ΔA_y . Errors in background subtraction in the DIFF spectra are primarily statistical. Small nonstatistical uncertainties may arise from the relative normalizations. Larger nonstatistical uncertainties exist in the background subtraction when generating the SUM spectra, for example, due to the difference in peak shapes. However, the effect of these uncertainties on ΔA_y is small because ΔA_y is dominated by the relatively poor statistics in DIFF spectra. A statistically weighted average of A_y was calculated. Consistent results within error bars were attained when the asymmetry was calculated either from the channels within the half-width of the elastic peak, or slightly larger regions, or from using a peak-fitting method. (At all angles the elastic peak was clearly visible in the SUM spectra.)

FIG. 1. Typical foreground- and background-subtracted missing-mass spectra for pion scattering from polarized $^{13}\text{C}_4\text{H}_{10}\text{O}$: (a) thick line, full spectrum; thin line, Cu background spectrum; (b) thick line, spectrum with Cu background subtracted; thin line, oxygen background spectrum; (c) thick line, spectrum with Cu + ^{16}O background subtracted.

The angular distributions of A_y at $T_\pi=132$ MeV for both π^- and π^+ scattering from this experiment are presented in Fig. 2. Nonzero A_y were observed for π^- scattering at $T_\pi=132$ MeV at angles near the first and second minima of $d\sigma(\theta)/d\Omega$, $\approx 60^\circ$ and $\approx 100^\circ$, respectively, whereas for π^+ scattering the A_y were consistent with zero at all angles. A larger A_y is expected and observed for π^- scattering than for π^+ scattering because there is an excess neutron in ^{13}C to which a π^- couples more strongly than a π^+ in the region of the P_{33} resonance.¹¹ Measurements were also done at $T_\pi=226$ MeV for π^+ and at $T_\pi=231$ MeV for π^- . Asymmetries (not shown) consistent with zero were found for both π^+ and π^- in the angular range of 40° to 80° at these energies.

The A_y from the search for predicted large values in π^- scattering near the second minimum of $d\sigma(\theta)/d\Omega$, $1.75 < q < 2.05$ fm $^{-1}$, were all found to be very small (Fig. 3). Specifically, at $T_\pi=165$ MeV our data are consistent with zero, a result similar to that found in the experiment⁴ on ^{15}N .

The error bars shown in Figs. 2 and 3 include only the statistical and background subtraction errors. Systematic errors in deriving the yields of the scattered pions (due to the uncertainties in the absolute beam flux, target thickness, and solid angle) cancel in the calculation of A_y [Eq. (3)]. The uncertainty in the determination of the target polarization was estimated to be 3%.

FIG. 2. Asymmetries A_y for elastic scattering of (a) π^- and (b) π^+ from ^{13}C at $T_\pi=132$ MeV. The curves are from DWIA calculations of this work (solid lines) and from predictions of Mach (Ref. 6) with densities due to Tiator (Ref. 17) (dashed lines) and with CK (Refs. 14 and 15) densities (chain-dashed lines).

In an attempt to reproduce the data, we have calculated¹² theoretical A_y using a model which employs a first-order optical potential. We used the optical-model program¹³ PIPIT (which does not include spin transfer) in conjunction with the inelastic-scattering code ARPIN.¹⁴ The spin-independent and spin-dependent parts of the elastic transition amplitude were obtained from ARPIN, and $d\sigma(\theta)/d\Omega$ and A_y were calculated in the distorted-wave impulse approximation (DWIA) with the distorted waves from PIPIT. The pion-nucleon t matrix was calculated at an energy below the actual pion-nucleon center-of-mass energy which appears to correct for some second-order effects. We found that at $T_\pi=132$ MeV an energy shift of 14 MeV for π^+ and of 4 MeV for π^- gave better fits with the elastic-scattering cross sections than the 20-MeV shift used¹⁰ at 162 MeV. We chose the difference of 10 MeV between the values for π^+ and π^- to be of the order of the π -nucleus Coulomb energy differences at the nuclear surface. A Gaussian off-shell model¹³ was employed with a momentum range parameter^{12,13} of 3×10^{-6} MeV $^{-2}$ at all energies.

At small momentum transfers q (scattering angles below 70°), where the Cohen-Kurath (CK) model¹⁵ provides us with reliable ground-state (g.s.) spin transition densities, we found reasonable agreement between the data at 132 MeV and our calculations (Fig. 2, solid lines). However, at large q (scattering angles of $\approx 100^\circ$), these calculations give incorrect signs for A_y . This failure is not unexpected because at large q the A_y depend strongly on both the reaction mechanism and the nuclear-structure model. We note that standard nuclear-structure models have thus far failed to reproduce

FIG. 3. A_y for elastic scattering of π^- from ^{13}C at energies across the [3,3] resonance at momentum transfers near the second minimum of the differential cross sections. The curves at 114 and 165 MeV are the predictions of Thies using the Δ -hole model (Ref. 5) (dotted lines) and the closure approximation to this model (chain-dotted lines). The chain-dashed lines are calculations of Mach (Ref. 6) with CK (Refs. 14 and 15) densities.

the measured magnetic form factor¹⁶ for $q > 1.6 \text{ fm}^{-1}$.

With the CK densities, Mach⁶ provided a prediction (chain-dashed curves in Figs. 2 and 3), based on a first-order optical potential as above, but including a phenomenological ρ^2 term which was adjusted to fit $d\sigma(\theta)/d\Omega$ at various energies. Here ρ is the nuclear density. Mach's predictions yield values of A_y similar to our calculations except at $\theta_{\text{c.m.}}$ near 55° . The fits with the elastic cross sections are generally better in the calculations of Mach than in our calculations, which predict a deeper first minimum than observed experimentally.

Additional calculations (dashed lines in Fig. 2) were performed by Mach with the same reaction model, but with densities provided by Tiator.¹⁷ These densities had been derived in an attempt to reproduce the anomalously low cross sections for photoproduction of charged pions on ^{13}C . The DWIA curves from these calculations are in disagreement with the data around 60° and also at the larger angles for π^- ; for π^+ a small peak is predicted at 95° which is consistent with the data although the error bars do not rule out zero A_y .

The large differences between the results of these calculations with the Tiator densities¹⁷ (dashed curves) and the CK densities^{14,15} (chain-dashed curves) demonstrate a strong dependence of A_y on the nuclear-structure model. However, the $d\sigma(\theta)/d\Omega$ (for both π^- and π^+) calculated with the two densities are almost identical. A wave-function dependence of A_y was also found in work¹⁸ on ^6Li .

The small A_y observed in the energy-dependence data and some theoretical predictions are shown in Fig. 3. At 165 and 114 MeV the data disagree with the theoretical curves obtained with CK densities^{14,15} by Mach (chain-dashed curves) and very similar ones obtained by us (not shown). Δ -hole model predictions of Thies and co-workers⁵ are also available at some of these energies and shown as dotted lines (full calculation) and chain-dotted lines (closure approximation). The wave functions used in these two Δ -hole calculations are again different from those of CK and Tiator. But the large difference in the predicted A_y (Fig. 3) from two different approaches to the reaction mechanism shows that the A_y are sensitive to the reaction model used. At 165 MeV the data show a preference for the closure approximation calculation. Δ -hole model calculations are not yet available at the other energies.

Further data on polarized ^{13}C have been taken at 100 MeV at TRIUMF (Ref. 19) and at 162 MeV at LAMPF.²⁰ Both data sets are presently being analyzed.

The asymmetry data of this and other recent work^{4,18} are not yet understood theoretically. They contain new information on the nuclear spin transition density and the pion-nucleus reaction mechanism. Further theoretical effort is needed to describe the high- q behavior of the

nuclear transition density, and specifically, its isoscalar spin-dependent part. Once that task is accomplished, our data may provide tests of pion-nucleus interaction theories which include higher-order terms such as the Δ -nucleus spin-orbit force.

We wish to thank Dr. R. Mach and Dr. M. Thies for permission to present the results of their theoretical calculations and Dr. P. J. Ellis for a critical reading of the manuscript. We also acknowledge a grant for computing time from the Minnesota Supercomputer Institute. This work was supported in part by the U. S. Department of Energy, the University of Minnesota Graduate School, and the Robert A. Welch Foundation.

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Analyzing Powers for Pion Charge Exchange on Polarized ^{13}C

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(Received 13 September 1990)

Results of the first pion single-charge-exchange experiment on a polarized nuclear target are reported. Analyzing powers A_y for the (π^+, π^0) reaction at $T_{\pi^+} = 163$ MeV on a polarized ^{13}C target were measured over an angular range between 20° and 60° in the laboratory system. Calculations in the distorted-wave impulse approximation do not reproduce these new data.

PACS numbers: 25.80.Fm, 24.10.Eq, 24.70.+s, 27.20.+n

We report first results arising from a new approach to the study of isovector spin-dependent interactions of pions in nuclei. These results are obtained from a measurement of the analyzing power of the (π^+, π^0) reaction on a transversely polarized ^{13}C target at a beam energy of 163 MeV.

Parity and rotational invariance determine the elementary pion-nucleon interaction t matrix to be of the form

$$t_{ba} = f(\theta) + ig(\theta)\hat{n} \cdot \sigma, \quad (1)$$

where $\hat{n} = (\mathbf{k} \times \mathbf{k}')/|\mathbf{k} \times \mathbf{k}'|$ ($\mathbf{k}$ and $\mathbf{k}'$ are the momenta of the incident and outgoing pions), and σ is the Pauli spin-or for the nucleon. The complex amplitudes $f(\theta)$ and $g(\theta)$ each have isoscalar and isovector parts. Elastic pion scattering is primarily sensitive to the isoscalar terms, and analyzing powers for $\pi^\pm$ elastic scattering at energies near the P_{33} resonance from polarized protons¹ and polarized nuclei in the $1p$ shell² have recently been reported. Although the asymmetries from the elementary process are sizable, those for spin- $\frac{1}{2}$ nuclear targets were found to be small.^{2,3} The interpretation of these results is not yet clear.

There is currently very little information on the isovector part of $g(\theta)$ since pion single-charge-exchange (SCX) cross sections at forward angles are dominated by the isovector part of $f(\theta)$ and no experiments to date

have isolated a transition dominated by spin transfer. However, SCX reactions on targets with spin create new possibilities. In the case of spin- $\frac{1}{2}$ targets, the pion-nucleus amplitude may be written in a form similar to Eq. (1), but with effective-medium-modified amplitudes $F(\theta)$ and $G(\theta)$ replacing the elementary ones. In addition to cross sections, the amplitudes yield analyzing powers given by (with 100% target polarization)

$$A_y(\theta) = \frac{(d\sigma/d\Omega)_\uparrow - (d\sigma/d\Omega)_\downarrow}{(d\sigma/d\Omega)_\uparrow + (d\sigma/d\Omega)_\downarrow} = \frac{2\text{Im}(FG^*)}{|F(\theta)|^2 + |G(\theta)|^2}, \quad (2)$$

where the arrow indicates the nucleon spin direction relative to $\hat{n}$ and the denominator is equal to the spin-averaged cross section. It is important to note from Eq. (2) that the analyzing power A_y is sensitive to the important phase relationship between $F(\theta)$ and $G(\theta)$. Our experiment provides information on the isovector part of that phase in the nuclear medium for the first time.

The ^{13}C spin-parity of $\frac{1}{2}^-$ keeps the number of spin-dependent observables to a minimum and therefore represents a sound starting point for exploring pion-nucleus spin physics. The isobaric-analog state (IAS) transition to the ground state of ^{13}N has minimal background, and the $^{13}\text{C}(\pi^+, \pi^0)$ unpolarized cross sections have been

previously measured at 165 MeV.⁴

Measurements were made at the low-energy pion channel at the Clinton P. Anderson Meson Physics Facility (LAMPF) with the LAMPF π^0 spectrometer⁵ which was positioned at laboratory scattering angles of 25°, 38°, and 55°. It was set at a distance of 1.5 m from the target for the 25° measurements and at 1.0 m for the 38° and 55° measurements. The angular acceptance was about 24° at the 1-m setting and about 18° at 1.5 m. The angular resolution of the spectrometer was about 6°, and two or three separate angles were binned from the data at each spectrometer setting.

The target material consisted of about 10 cm³ of frozen beads, about 1.5 mm in diameter, composed of ethylene glycol OH-(CH₂)₂-OH doped with 7×10¹⁹ molecules/ml of EHBA-Cr^(v).⁶ The carbon was enriched to 99% ¹³C atoms. The beads were contained in a Teflon basket which was placed inside a thin-walled copper cell. The cell was 2 cm thick and the effective thickness of the carbon was about 620 mg/cm². The target cell was cooled to about 0.5 K with a ³He evaporation refrigerator. A polarization normal to the scattering plane of about 27% was induced by using the dynamic nuclear polarization technique⁷ in a uniform magnetic field of 2.5 T. The target polarization was measured with the nuclear-magnetic-resonance (NMR) method. The NMR signal was normalized by using the thermal equilibrium technique.⁷

The relative π^+ beam intensity was measured by means of two toroidal current monitors through which the primary proton beam passed and by an ion chamber through which the π^+ beam passed. The absolute beam intensity was determined periodically by measuring the ¹¹C(β) activity produced in thin scintillator disks.⁸ It was helpful for comparisons of the derived cross sections with those from Ref. 4, but was not needed for the analyzing powers.

Backgrounds arising from accidental two-photon coincidences and from the cryostat were subtracted from the raw data. The background spectra were obtained by using a replica of the real polarized target with water replacing the ethylene glycol target beads and the ³He refrigerant. The yield due to non-¹³C contaminants in the IAS region is small, due to a favorable Q value for the IAS transition of +2.89 MeV; the nearest significant contaminant reaction ³He(π^+ , π^0) $3p$ is separated from the IAS by 4.7 MeV. The spectra were then analyzed by fitting one or more peaks, along with background functions, to the low-excitation region. The shape of the peak was determined from a Monte Carlo simulation of the entire experimental arrangement and it correctly reproduces the signal shape observed with the same experimental apparatus for the elementary $\pi^-p \rightarrow \pi^0n$ reaction.⁹ The peak shape had a full width at half maximum of about 5 MeV.

Figure 1 shows spectra for detected events with $X = |E_1 - E_2|/(E_1 + E_2) \leq 0.15$, where E_1 and E_2 are

FIG. 1. Spectra for the ¹³C(π^+ , π^0) reaction at 163 MeV and at 22.4°. The solid curve is the fitted sum of three peaks shown individually as dash-dotted curves. The dashed curve represents the fitted nuclear background. The crosses represent the data prior to subtraction of the instrumental background.

the laboratory energies of the two photons resulting from the π^0 decay.⁵ Structure that can be associated with three separate states is evident. The spectra cannot be well described with fits based on the assumption of a single peak with a phenomenological background, and the extracted cross sections were typically less than those reported in an earlier experiment.⁴ The kinematics of such a peak were also inconsistent with ¹³C. However, good fits were obtained by including peaks for two excited states as well. The positions of the three peaks were found to follow the kinematics of the ground state and states near 3.5- and 7.4-MeV excitation in ¹³C. The summed cross sections of the ground state and 3.5-MeV state are in good agreement with the earlier results.⁴

The features seen in Fig. 1 were present in all of the other spectra as well. Separate fits were made to the spin-up and spin-down spectra. We assumed that the same shape of the background, adjusted only in normalization, could be used for both spin orientations of each angle bin. Various phenomenological forms for the background were tested. A third-order polynomial form produced results that agreed with those obtained with the adopted exponential-plus-constant form. Both of these forms had essentially zero magnitudes at the ¹³N proton-decay threshold of 1.94 MeV.

The summed yields from the spin-up and spin-down

spectra agree with the yields obtained from independent fits to the summed spectra. The events in the empirical difference spectra were too few to be useful for fitting directly. However, the differences in the fits to the spin-up and spin-down spectra were consistent with these difference spectra.

The analyzing powers were computed from the expression

$$A_y(\theta) = (N^+ - N^-)/(N^+P^- + N^-P^+), \quad (3)$$

where N^+ (N^-) is the normalized yield of good charge-exchange events with the target polarized parallel (antiparallel) to the normal to the scattering plane, and P^+ and P^- are the corresponding target polarization values. The features of the analyzing powers were stable to changes in details of the fitting procedure such as the forms of the background and constraints on the absolute or relative positions of the peaks. Fits that included the $\frac{1}{2}^+$ state at 2.36 MeV gave no statistical improvement and were otherwise unsatisfactory. This state and its analog in ^{13}C are known to be very weakly populated in inelastic-scattering and charge-exchange reactions.¹⁰⁻¹² The observed first-excited state corresponds to the collectively enhanced $\frac{1}{2}^-$, $\frac{5}{2}^+$ doublet separated by about 3.5 MeV from the IAS. The peak at the best-fit excitation energy of 7.4 MeV involves transitions to several states.

The experimental results are shown in Figs. 2 and 3. The cross sections for the excited state are comparable to

those for the IAS, but differ in their angular dependence. The analyzing powers for the two states are quite different. At this time the relative contributions of the $\frac{1}{2}^-$ and $\frac{5}{2}^+$ states to the yields for the 3.5-MeV group are unknown.

The error bars include statistical and fitting uncertainties associated with the determination of N^+ and N^- , as well as uncertainties arising from background subtractions. The fitting uncertainty was estimated from the results obtained from variations of the peak-fitting procedures and ranged from 0.05 to 0.11. Many of the uncertainties that apply to differential cross sections cancel out in the expression for $A_y(\theta)$. An estimate of the systematic uncertainty of A_y for each angle setting of the spectrometer was obtained from comparisons of the analyzing powers extracted from sets of runs with the same polarization orientation. False (nonzero) asymmetries can arise from fluctuations in the ion chamber and beam-toroid counters used to monitor the relative beam flux, fluctuations in the steering of the beam, and statistical uncertainties associated with the determination of the target polarization. Such systematic errors of 0.04–0.06 were combined in quadrature with the statistical errors associated with Eq. (3). Not included in Figs. 2 and 3 is an additional systematic uncertainty in the target polarization, estimated to be about 4.0%. This uncertainty arises from possible errors in the temperature calibration for the thermal equilibrium measurements as well as from biases in estimating the back-

FIG. 2. Cross sections and analyzing powers for the $^{13}\text{C}(\pi^+, \pi^0)$ reaction at 163 MeV to the isobaric-analog state. The cross sections from Doron *et al.* (Ref. 4) are shown as open squares. The curves are results of DWIA calculations by Siegel (solid), and by Mach (CK wave functions, dashed; Tiator wave functions, dot-dashed).

FIG. 3. Cross sections and analyzing powers for the $^{13}\text{C}(\pi^+, \pi^0)$ reaction at 163 MeV to the $\frac{1}{2}^-$, $\frac{5}{2}^+$ doublet at 3.5 MeV. The solid curves, for the $\frac{1}{2}^-$ state only, have the same meaning as in Fig. 2.

ground under the peak in the NMR spectra.

The cross sections and analyzing powers are compared with the results of theoretical distorted-wave impulse-approximation (DWIA) calculations in Figs. 2 and 3. The calculations by Siegel reproduce the observed IAS cross sections well.¹³ Cohen and Kurath (CK) wave functions¹⁴ were used for the nuclear structure. Although the results follow the trend of the analyzing powers at forward angles, the magnitudes are typically too large and the structures are too sharp. The calculations also do not describe well the excited-state cross sections and analyzing powers, although the $\frac{5}{2}^+$ transition has not yet been included. Similar calculations by Mach with both CK and Tiator wave functions¹⁵ for the IAS transition give a better, but not perfect, description of the analyzing powers; however, the cross sections are less satisfactory.¹⁶

The DWIA calculations of Siegel and Mach differ primarily in the detailed modeling with which the elementary pion-nucleon amplitudes are converted to the pion-nucleus amplitudes $F(\theta)$ and $G(\theta)$. Both sets of calculations appear not to be strongly sensitive to the assumed model of nuclear structure, at least not to those that are limited to wave functions in the $1p$ shell (cf., e.g., Ref. 13). Typically, the analyzing powers are less sensitive to changes of the models than are the cross sections.

The magnetic form factor for electron scattering from ^{13}C , which is also sensitive to spin-dependent effects, appears to require nuclear structure wave functions that go beyond the $1p$ shell.¹⁷ Although the momentum transfers of greatest sensitivity are a bit larger than those reached by the present data (about 1.4 fm^{-1}), a satisfactory description of the present analyzing-power data may require an extended model of nuclear structure. Attention should also be given to as yet unknown modifications of the elementary pion-nucleon interaction by the nuclear medium, especially its spin-dependent features.

This work was supported in part by the U.S. Department of Energy, the National Science Foundation, and the Robert A. Welch Foundation. We wish to thank the many members of the LAMPF staff for the tireless efforts that helped make this experiment possible, and

the LAMPF management for their support and encouragement.

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Evidence for Direct Triton Knockout in the ${}^4\text{He}(\pi, \pi' t)p$ Reaction

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(Received 18 May 1992)

Angular correlation functions for the ${}^4\text{He}(\pi^\pm, \pi^\pm' t)p$ reaction at the incident energy $T_\pi = 180$ MeV and at four pion scattering angles have been measured. The ${}^4\text{He}(\pi^\pm, \pi^\pm' t)p$ data complement previous ${}^4\text{He}(\pi^\pm, \pi^\pm' p)t$ results by greatly extending the available range of proton emission angles. We calculate angular correlation functions of the cross sections with three different quasifree knockout models, and we show that direct triton knockout is crucial to an understanding of the data.

PACS numbers: 25.80.Hp, 25.10.+s, 27.10.+h

Knockout of α particles from nuclei by the $(p, p'\alpha)$ and $(\alpha, 2\alpha)$ reactions have been studied for a wide range of targets and incident energies [1] and have provided information on the existence of α clusters in the nuclear surface. Much less is known about knockout of the three-nucleon clusters, ${}^3\text{He}$ and ${}^3\text{H}$ (t). In this work, we investigate triton and proton knockout from ${}^4\text{He}$ using π^+ and π^- beams at incident energy $T_\pi = 180$ MeV, near the P_{33} [$\Delta(1232)$] π -nucleon resonance. ${}^4\text{He}$ is the best possible target for a study of triton and proton knockout because approximately 90% of the total proton momentum distribution in ${}^4\text{He}$ can be attributed to the $p+t$ state (at small relative momentum) [2]. We show that the strong isospin dependence of the elementary π -nucleon force can be used to distinguish between direct proton knockout [3] and triton knockout, and we find that direct triton knockout is crucial to an understanding of the data.

If the ${}^4\text{He}(\pi, \pi' p)$ reaction were to proceed exclusively by quasielastic π -proton scattering, we would expect a cross-section ratio $\sigma(\pi^+, \pi^+ p)/\sigma(\pi^-, \pi^- p)$ equal to 9 because the ratio of π^+ -proton to π^- -proton elastic scattering amplitudes is 3 for the P_{33} resonance. However, if the reaction were to proceed exclusively by quasielastic π -triton scattering, we would expect a cross-section ratio $\sigma(\pi^+, \pi^+ t)/\sigma(\pi^-, \pi^- t)$ equal to 25/49 ($\approx 1/2$) because the π^- interacts preferably with the two neutrons of the triton whereas the π^+ interacts preferably with the one proton. Early experiments [4] studying pion-induced knockout reactions on ${}^4\text{He}$ at 110 and 160 MeV used cloud chambers, but the data were not sorted according to the angle of the knocked-out nucleon N . This fact limited the theoretical analysis to that of the $(\pi, \pi' N)$ cross sections integrated over the nucleon emission angle. Calculations by Mach *et al.* [5] indicated that a three-nucleon exchange (knockout) amplitude is important at large momentum transfer. However, the calculations failed to reproduce the ratio of total cross sections

and this was interpreted as evidence for considerable initial- and/or final-state interaction effects. Tritons have been identified in the ${}^{12}\text{C}(\pi^\pm, \pi^\pm' t){}^9\text{B}$ [6] reaction but the statistics were insufficient to warrant a firm conclusion and no attempt was made to model the reaction.

The experiment [3] was performed using the energetic pion channel and spectrometer systems (EPICS) [7] at the Clinton P. Anderson Meson Physics Facility (LAMPF). EPICS was positioned at four angles $\theta_\pi^{\text{lab}} = 30^\circ, 40^\circ, 60^\circ$, and 80° on the left-hand side of the beam. In order to detect the particles emitted in coincidence with the pions, an array of plastic scintillators, each with a solid angle of 57 msr, was placed in the evacuated scattering chamber to the right-hand side of the beam at the angles $\theta^{\text{lab}} = -30^\circ, -45^\circ, -60^\circ, -75^\circ$, and -90° . The experimental conditions and the analysis procedure were the same for incident π^+ and π^- . Angular correlation functions for the π -proton coincidence data from a recent ${}^4\text{He}(\pi^\pm, \pi^\pm' p)t$ experiment have been published by Jones *et al.* [3]. We have reanalyzed the raw data of that experiment and extracted π -triton coincidences.

The particle-dependent pulse height from the plastic scintillators and the particle's time of flight allowed identification and determination of the energy of the protons and tritons. In a plot of particle energy loss in the scintillators versus excitation energy $E_x({}^4\text{He})$, the $p+t$ final state (with a separate pulse-height and time-of-flight signature for protons and tritons) was cleanly separated from particles from other reaction branches. $\theta_p^{\text{c.m.}}$ ($\theta_t^{\text{c.m.}}$) is the proton (triton) ejectile angle in the c.m. of the recoiling mass-4 system. In the present work, the $(\pi, \pi' t)$ data are plotted together with the $(\pi, \pi' p)$ data as functions of $\theta_p^{\text{c.m.}}$, since $\theta_p^{\text{c.m.}} = \theta_t^{\text{c.m.}} + 180^\circ$. Some data had been obtained in Ref. [3] due to π -proton coincidences observed in detectors placed at angles larger than 90° . Those data have large error bars and correspond to low-

energy protons which were not well separated from the background. Data for the mirror reaction branch $n + {}^3\text{He}$ have not been extracted from this experiment because these events fell below detector threshold. A more complete description of the experiment can be found in Ref. [3].

The incoming pion of total energy and momentum $(E_\pi, \mathbf{k}_\pi)$ scatters from ${}^4\text{He}$ such that the pion's outgoing energy and momentum are $(E'_\pi, \mathbf{k}'_\pi)$. Energy ΔT_π and momentum $\mathbf{q}$ are transferred to the nucleus such that $\Delta T_\pi = E_\pi - E'_\pi$ and

$$\mathbf{q} = \mathbf{k}_\pi - \mathbf{k}'_\pi = \mathbf{k}_p + \mathbf{k}_t, \quad (1)$$

where $\mathbf{k}_p$ and $\mathbf{k}_t$ are the momenta of the proton and triton in the final state. The excitation energy E_x in ${}^4\text{He}$ can be expressed in terms of ΔT_π and q by

$$E_x({}^4\text{He}) = [(\Delta T_\pi + m_a)^2 - q^2]^{1/2} - m_a, \quad (2)$$

where m_a is the mass of the ${}^4\text{He}$ nucleus.

In order to obtain the double-differential cross sections (angular correlation functions) shown in Fig. 1, we have integrated the triple-differential cross sections $d^3\sigma/d\Omega_\pi dE_x$ over the region of $E_x({}^4\text{He})$ between 30 and 40 MeV. The condition that $E_x({}^4\text{He})$ be greater than 30 MeV allowed us to identify recoiling tritons. At all pion angles, the π^+ angular correlation data (solid dots) peak near $\theta_p^{\text{c.m.}} = 0^\circ$ where proton knockout is expected to have its maximum. In sharp contrast, the π^- angular correlation data (open dots) show a cross section near $\theta_p^{\text{c.m.}} = 0^\circ$ that is often much more than a factor of 9 smaller than for π^+ . This observation is discussed extensively in Ref. [3]. However, the π^- data do show maxima near $\theta_p^{\text{c.m.}} = 180^\circ$ because direct triton knockout is expected to generate a peak in the angular correlation. The π^+ data also display relative maxima near 180° but the cross sections for direct π^- -triton knockout are larger.

We have modeled the ${}^4\text{He}(\pi, \pi'p)t$ reaction using the sum of the amplitudes for two processes: direct proton knockout and direct triton knockout. Angular correlation functions were calculated in this new two-amplitude quasifree (TAQ) model using the equation

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

The function $\phi(k)$ is a momentum-space wave function of the $p+t$ system, and for the present calculations, we use a Gaussian wave function which reproduces the charge form factor of ${}^4\text{He}$. The momenta in Eq. (3) are not mutually independent as can be seen from Eq. (1). 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. The π -proton amplitudes $f_{\pi p}$ were calculated from Ref. [8] and the π -triton amplitudes $f_{\pi t}$ were calculated according to Ref. [9]. This model gives peak values of the cross section when k_t or k_p are zero; i.e., the limiting cases of Eq. (3) are two independent quasifree scatterings. This model differs from other quasifree models by including the term with $f_{\pi t}$ in Eq. (3). All TAQ model calculations were

FIG. 1. Double-differential cross sections for the reactions ${}^4\text{He} + \pi^+ \rightarrow p + t + \pi^+$ (solid dots) and ${}^4\text{He} + \pi^- \rightarrow p + t + \pi^-$ (open dots) for E_x integrated between 30 and 40 MeV. The solid curves represent our TAQ double-scattering calculations for π^+ (thin lines) and for π^- (thick lines). At $\theta_\pi^{\text{lab}} = 80^\circ$ and 60° the dot-dashed (π^+) and dashed (π^-) curves show the TAQ single-scattering calculation. At $\theta_\pi^{\text{lab}} = 40^\circ$ and 30° the dotted (π^+) and long-dashed (π^-) curves represent the THREEDEE model calculation. Quasielastic proton scattering dominates at $\theta_p^{\text{c.m.}} = 0^\circ$ whereas quasielastic triton scattering dominates at $\theta_p^{\text{c.m.}} = 180^\circ$.

done for $E_x = 35$ MeV.

The TAQ model calculations represented by the dot-dashed (π^+) and dashed (π^-) lines in Fig. 1 (only for the $\theta_\pi^{\text{lab}} = 80^\circ$ and 60° panels) assume a single-scattering approximation. This version of the TAQ model describes a two-body scattering problem which is being truncated, not the full scattering from four nucleons. In order to address the question of the degree of validity of the single-scattering approximation, which may not be accurate because the π -nucleon interaction is very strong, we have carried out a double-scattering TAQ calculation. The double-scattering calculations are shown as solid thin (π^+) and thick (π^-) lines in Fig. 1 (for all θ_π^{lab}) and approximately account for a "shadowing" effect due to scattering from the spectator particle. Our present TAQ

calculations do not sufficiently describe the π^- -induced reaction. The inclusion of a shadowing effect does not sufficiently decrease the scattering probability to the level shown by the experiment, especially at $\theta_p^{c.m.} = 0^\circ$. At this point, our calculation with double scattering should be taken only as an indication of the size of the effect. For example, for π^- scattering to $\theta_\pi^{lab} = 80^\circ$ and $\theta_p^{c.m.} = 0^\circ$, the effect is to decrease the cross section by roughly 20%.

Calculations from the one-nucleon knockout model THREEDEE [10] are represented by dotted (π^+) and long-dashed lines (π^-) in Fig. 1 (only for $\theta_\pi^{lab} = 30^\circ$ and 40°) and compared to the TAQ double-scattering predictions (solid lines). The THREEDEE calculations are made in the framework of the impulse approximation. They include (using a factorization approximation) the distortions of the incoming pion and target-nucleus system, the outgoing pion and residual-nucleus system, and the knocked-out proton and residual-nucleus system. The THREEDEE predictions for double-differential cross sections depend strongly on various distortions [3]. The back-angle rise in the THREEDEE predictions near $\theta_p^{c.m.} = 180^\circ$ is a consequence of distortions, not of triton knockout. These calculations do not include a π -triton amplitude $f_{\pi t}$ as in Eq. (3). The THREEDEE calculations at back angles are an order of magnitude smaller than the data for π^- .

One can estimate the effect of the momentum distribution on quasifree scattering cross sections by using the ansatz that the recoil momentum of the spectator particle (k_{spec}) is equal to its momentum before scattering. We calculated excitation energies where a $p+t$ momentum distribution has its maximum value ($k_{spec}=0$) and half-maximum value [2] ($k_{spec}=0.45 \text{ fm}^{-1} \approx 90 \text{ MeV}/c$). The values of E_x for $k_{spec}=0$ are listed in Table I in the columns denoted by $E_x^{q.f.}$. Deviations from $E_x^{q.f.}$ for E_x such that $k_{spec}=90 \text{ MeV}/c$ are indicated by the superscripts and subscripts in Table I. For example, at $\theta_\pi^{lab} = 40^\circ$, quasifree proton knockout occurs with maximal probability when $E_x = 34 \text{ MeV}$. With $E_x = 33 \text{ MeV}$, direct triton knockout occurs with roughly one-half of the maximal probability because the (spectator) proton is

TABLE I. The predicted centroids of quasifree peaks in the excitation energy spectra are given for all pion scattering angles in columns labeled $E_x^{q.f.}(\pi, \pi'p)$ and $E_x^{q.f.}(\pi, \pi't)$. For these values, the spectator particle is emitted with zero momentum ($k_{spec}=0$). The superscripts and subscripts give, if added to $E_x^{q.f.}$, the excitation energies corresponding to $k_{spec} \approx 90 \text{ MeV}/c$, as discussed in the text. Subscripts are omitted when breakup is energetically forbidden. The momentum transfers q are given for $E_x = 35 \text{ MeV}$.

$\theta_\pi^{lab} \text{ (deg)}$	$q \text{ (fm}^{-1}\text{)}$	$E_x^{q.f.}(\pi, \pi'p) \text{ (MeV)}$	$E_x^{q.f.}(\pi, \pi't) \text{ (MeV)}$
30	0.73	28^{+18}	22^{+9}
40	0.94	34^{+18}_{-12}	22^{+11}
60	1.35	47^{+18}_{-12}	23^{+11}
80	1.70	60^{+18}_{-22}	26^{+12}

emitted with $\approx 90 \text{ MeV}/c$. Also given in the table is the momentum transfer q for each of the pion scattering angles with $E_x = 35 \text{ MeV}$.

We define an isospin (T) asymmetry $A_T(\theta_p^{c.m.})$, in analogy with the spin observable A_p , with the equation

$$A_T(\theta_p^{c.m.}) = \frac{\sigma(\pi^+, \pi^+X) - \sigma(\pi^-, \pi^-X)}{\sigma(\pi^+, \pi^+X) + \sigma(\pi^-, \pi^-X)}, \quad (4)$$

where $X=p$ or t . In the plane-wave impulse approximation (PWIA) and for P_{33} resonance dominance, the observable $A_T(\theta_p^{c.m.})$ is isotropic and equal to $+0.8$ for pure quasielastic proton knockout. For pure quasielastic triton knockout, we expect $A_T(\theta_p^{c.m.})$ to be isotropic and equal to ≈ -0.3 . These results are *independent* of the scattering angle of the pion and proton. Moreover, if the pion scattering excites ^4He to a resonance state with pure isospin, its decay is governed exclusively by the properties of that state, and we expect $A_T=0$. Thus, exclusive, kinematically complete π^+ and π^- scattering should easily distinguish between proton knockout, triton knockout, or resonance formation and decay for these reasons: the prediction of isotropy in $A_T(\theta_p^{c.m.})$ in the

FIG. 2. Isospin asymmetry $A_T(\theta_p^{c.m.})$ [Eq. (4)] for the reactions $^4\text{He} + \pi^\pm \rightarrow p + t + \pi^\pm$, for E_x integrated between 30 and 40 MeV. The data show large isospin asymmetries, changing from $+1.0$ near $\theta_p^{c.m.} = 0^\circ$ to -0.6 near $\theta_p^{c.m.} = 180^\circ$. The solid and dashed lines of the TAQ model qualitatively describe the data with and without double scattering and show the importance of direct triton knockout near $\theta_p^{c.m.} = 180^\circ$. The dot-dashed lines represent proton knockout calculations (with distortions) using THREEDEE [10]. These asymmetries are essentially isotropic, because that model does not include a π -triton amplitude such as $f_{\pi t}$ in Eq. (3).

case that a single amplitude is involved in the scattering, and the large values and different signs of asymmetry for quasifree proton and triton scattering.

The data for $A_T(\theta_p^{c.m.})$ in Fig. 2 vary strongly with $\theta_p^{c.m.}$ from near +1.0 in the kinematic region of quasifree proton knockout ($\theta_p^{c.m.} = 0^\circ$), to about -0.6 in the kinematic region of quasifree triton knockout ($\theta_p^{c.m.} = 180^\circ$). This result requires that at least two amplitudes contribute to the reaction. The TAQ model with the π -triton scattering amplitude successfully describes the sign reversal of $A_T(\theta_p^{c.m.})$ with (solid lines) or without the shadowing effect (dashed lines). The prediction using THREEDEE (dash-dotted lines) with only a π -proton interaction is essentially isotropic (near the PWIA prediction of $A_T = +0.8$). This is our strongest evidence for direct triton knockout.

Use of different pion-nucleus optical potentials and proton-triton optical potentials in THREEDEE can affect the calculations of cross sections [3] by factors of 2 to 3; however, these changes yield values of $A_T(\theta_p^{c.m.})$ which differ by less than 2%. The THREEDEE model calculations deviate slightly from $A_T(\theta_p^{c.m.}) = +0.8$ because of distortions and/or contributions from the s -wave π -nucleon interaction. The dependence of $A_T(\theta_p^{c.m.})$ on variations of the TAQ model is also small, because shadowing effects in the TAQ model are similar for π^- - and π^+ -induced reactions.

While there is ample evidence from $A_T(\theta_p^{c.m.})$ that triton knockout is present, the TAQ model underestimates the magnitude of A_T near $\theta_p^{c.m.} = 0^\circ$ and 180° (Fig. 2). The TAQ description of the π^- -proton data near the quasifree proton angle is poor and the TAQ calculation of the π^+ -proton cross section (Fig. 1) varies with proton angle more slowly than the data. The TAQ model may be improved by use of ^4He wave functions such as in Ref. [2]. The largest variation between the model calculations is near $\theta_p^{c.m.} = 90^\circ$ and -90° , where interference effects in the TAQ model are maximized, but where there are currently no data.

Clearly, additional physics issues need to be considered. Of these, nuclear resonance states may be important, but based on a recent compilation and study [11], we expect that we avoid much of the complicated nuclear structure of ^4He below $E_x \approx 30$ MeV. Another possibility is a charge-exchange (n, p) process which is expected to be particularly strong near $\theta_p^{c.m.} = 0^\circ$ for π^- . The two-step charge-exchange reaction mechanism ($e, e'n$) followed by (n, p) was studied in a model of the exclusive reaction [12] $^4\text{He}(e, e'p)$. Calculations that combined the effects of (n, p) charge exchange, meson exchange, and proton rescattering showed that an (n, p) charge-exchange process increases the $^4\text{He}(e, e'p)$ cross section by about 10% [12]. Direct triton knockout was not included in that cal-

culation.

Kyle *et al.* [13] have modeled the $^{16}\text{O}(\pi^\pm, \pi^\pm p)$ reaction by including a Δ - N interaction. In that model a Δ -induced proton knockout amplitude interferes with the quasifree proton knockout process. Understanding of the present data for ^4He may improve with the application of such a model, but that model has not been extended yet to include a π -triton interaction.

We conclude that the isospin dependence of the π -triton interaction in the region of the $P_{3,3}$ resonance can be used to identify direct triton knockout from the nucleus. Experiments with π^+ and π^- on other nuclei in which tritons (and possible ^3He) are detected could provide evidence for the occurrence of preexisting clusters of mass 3. Exclusive scattering experiments with π^+ and π^- on light nuclei should allow us to refine reaction models and nuclear wave functions. For the $^4\text{He}(\pi^\pm, \pi^\pm t)p$ reaction, the direct π -triton scattering amplitude appears to be an essential component of the reaction mechanism.

This work was supported in part by the U.S. Department of Energy.

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Asymmetries for Elastic Scattering of π^+ from Polarized ^3He and the Δ -Neutron Spin-Spin Interaction

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(Received 22 November 1995)

Asymmetries for π^+ elastic scattering from polarized ^3He were measured across the $\Delta(1232)$ π -nucleon resonance region at incident energies $T_\pi = 142, 180$, and 256 MeV. Large discrepancies were found between the data and calculations that use the multiple scattering formalism and Faddeev wave functions. Inclusion of a Δ -neutron spin-spin interaction term in the calculations gives a greatly improved representation of the data. [S0031-9007(96)00229-3]

PACS numbers: 25.80.Dj, 13.75.Cs, 24.70.+s, 25.10.+s

In this Letter we report on the first measurement of asymmetries A_y for π^+ elastic scattering from polarized ^3He at incident energies which pass through the $\Delta(1232)$ π -nucleon resonance. We find evidence for the importance of the $\Delta(1232)$ -neutron spin-spin interaction in the nucleus. Knowledge of the strength of the spin-dependent (and spin-independent) parts of the Δ -nucleon interaction is needed for tests of meson-exchange [1] and quark models [2] of the baryon-baryon interaction.

Measurements on polarized ^3He recently became possible with the development of the high-density, optically pumped ^3He gas target at TRIUMF [3]. This target was used in a π^+ scattering experiment and very large values of A_y were found at $T_\pi = 100$ MeV [4].

These large values of A_y are in contrast with the generally small values obtained from scattering on p -

shell nuclei of spin $1/2$ [5–8]. The theoretically [9–11] unexpected small A_y for ^{15}N and ^{13}C imply shortcomings in our present understanding of either the π -nucleus interaction and specifically its spin-dependent part, or of the nuclear wave functions of these p -shell nuclei, or both. For the much simpler nucleus ^3He , reliable wave functions have been obtained by Faddeev calculations [12,13]. Thus spin-dependent effects in the π -nucleus interaction can be studied without large uncertainties in the nuclear structure. However, at 100 MeV the A_y for ^3He show only a slight dependence on the reaction model.

Thus measurements of π^+ elastic scattering from polarized ^3He at energies near the centroid and above the $\Delta(1232)$ resonance, where A_y is predicted [14,15] to be very sensitive to the details of the reaction model, are of great interest for a study of the spin-dependent parts of the

pion-nucleus interaction. We note that sensitivity to the small components of the ^3He wave function is predicted at $T_\pi \geq 256$ MeV.

The TRIUMF target was set up in the P³E area at LAMPF, where high beam fluxes were available across the region of the $\Delta(1232)$ resonance. The scattered pions were detected with the large acceptance spectrometer (LAS) [16]. Measurements were made at incident energies $T_\pi = 142, 180,$ and 256 MeV and laboratory scattering angles ranging from 40° to 100° . Some data were taken at 100 MeV and found to be in agreement with the results of Ref. [4].

The ^3He gas was contained in a cylindrical glass cell, about 4.8 cm in diameter and 6.5 cm in length. Target cells were made of quartz glass that was about 1.5 mm thick at the cylindrical cell walls and 0.4 mm thick at the hemispherical endcaps (where the pion beam entered and exited the cell). The cells were filled with 6 – 7 atm of ^3He gas, a trace of Rb, and a small amount of N_2 which served as a buffer gas. 8 – 10 W of polarized laser light at 795 nm (the $D1$ transition in Rb) from two argon pumped Ti:sapphire lasers and solid state diode laser arrays were used to polarize the Rb atoms in the target cell. The electron spin polarization of the Rb was transferred through Rb- ^3He collisions to the ^3He nucleus by the contact hyperfine interaction. The target cell was heated continuously in the target oven to a temperature of approximately 175°C in order to achieve the required Rb vapor density for the optical pumping. When the glass cell was hot, small amounts of ^3He leaked from the cell. Therefore, the pressure in the cell and the cell temperatures were monitored periodically so that a correction for the pressure loss could be made.

The target apparatus was modified during the experiment by the addition of a diode laser array [17]. The diode laser added to the optical pumping power and significantly increased the polarization after one of the argon lasers failed. ^3He polarization was typically 35% to 45% , sometimes reaching 50% . Since the helicity of the laser light determines the direction of the target polarization, the orientation of the ^3He spins (and thus the sign of A_y) was determined by use of a liquid crystal which transmits only left-hand circularly polarized light. One set of Helmholtz coils provided a vertical holding field for the polarization. Another set of Helmholtz coils provided a variable horizontal field component employed for changing the direction of the polarization. The magnitude of the polarization was measured using the nuclear magnetic resonance (NMR) technique of adiabatic fast passage (AFP) [3]. Absolute normalization factors for the NMR signals were obtained by comparing the NMR signals from the ^3He with the weak signals from the protons in a water-filled cell of the same dimension.

The LAS uses a magnetic quadrupole doublet, a magnetic dipole, scintillation detectors, and several sets of two-dimensional wire chambers in order to identify the scattered pions and to measure their momenta [16]. The

front wire chambers allow traceback of the scattered particle trajectories to a plane that intersects the center of the target perpendicular to the central ray of the LAS. The projections of the reaction vertices onto this plane were used to discriminate between events from ^3He and the glass in the end caps and the top and bottom of the cylindrical cell wall. Events from the left and right sides of the cylindrical wall could not be eliminated by software cuts. Thus the beam halo striking the sides of the cell was reduced by a lead collimator that was machined to match the beam divergence. In order to enable subtraction of the remaining background, spectra were taken at many angles with an evacuated target.

The top and center panels of Fig. 1 show yields as a function of the negative Q value of the reaction measured at 180 MeV and $\theta_{\text{lab}} = 50^\circ$, normalized to the integrated beam flux for the two target spin orientations. The target polarization parallel to the norm of the reaction plane is indicated by $\uparrow$, the one antiparallel by $\downarrow$. The ^3He elastic peak, centered at $Q = 0$, has a width of about 4 MeV (FWHM). The difference spectrum is shown in the bottom panel of Fig. 1. A large negative A_y is apparent in the region of the elastic peak from ^3He .

The experimental A_y was obtained using

$$A_y = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} \frac{1}{p}. \quad (1)$$

FIG. 1. Typical normalized energy spectra from elastic scattering of π^+ on the polarized ^3He target at $T_\pi = 180$ MeV and $\theta_{\text{lab}} = 50^\circ$. Top panel: target spin parallel ($\uparrow$); center panel: target spin antiparallel ($\downarrow$) to the normal to the reaction plane. The difference spectrum is shown in the bottom panel.

Here $N_{\uparrow}$ and $N_{\downarrow}$ are the normalized numbers of counts in the ^3He elastic peak with the ^3He spins oriented "up" and "down," respectively. p is the target polarization. Background events cancel in the difference $N_{\uparrow} - N_{\downarrow}$ and were subtracted before taking the sum. The theoretical A_y in pion scattering from a spin 1/2 nucleus can be written in terms of the complex spin-independent (F) and spin-dependent (G) scattering amplitudes as

$$A_y = \frac{2 \text{Im}(FG^*)}{(|F|^2 + |G|^2)}. \quad (2)$$

Experimental and theoretical angular distributions of A_y for π^+ elastic scattering at $T_{\pi} = 142, 180,$ and 256 MeV are presented in Fig. 2. The solid lines were obtained using multiple scattering theory and three-body Faddeev wave functions [12,13] for ^3He to calculate the first-order terms in F and G . The dashed lines employ a hybrid model (see below) that uses the first-order values of F and G but includes a second-order contribution to G from the Δ -neutron spin-spin interaction calculated in the plane wave impulse approximation (PWIA).

Neither the conventional multiple scattering calculations of Ref. [15] (Fig. 2, solid lines) nor those of one of us (W. R. G.) and of Ref. [18] (not shown) give a satisfactory description of A_y at 142 and 180 MeV. At both energies we observe large positive A_y near 80° as predicted by the calculation, but the maximum of A_y is shifted towards larger angles. At scattering angles near 60° the measured

FIG. 2. Asymmetry angular distribution for elastic π^+ scattering from polarized ^3He at $T_{\pi} = 142$ MeV (top), 180 MeV (center), and 256 MeV (bottom). Solid lines: Multiple scattering predictions of Ref. [15] using Faddeev wave functions. Dashed lines: Predictions of the hybrid model (see text).

A_y are negative at 142 and 180 MeV, in contradiction to any of the conventional model calculations which predict positive A_y between 100 and 180 MeV at these angles. Use of a simple s -state wave function for ^3He and the PWIA predicts positive A_y at all angles [14] (not shown) similar to the calculations using Faddeev wave functions (solid lines) at 142 and 180 MeV. At 256 MeV this simple model predicts positive A_y at all angles, whereas the multiple scattering calculations give negative A_y . The negative A_y at 256 MeV (but not at 142 and 180 MeV) can also be obtained by modifying the real part of F in a way that accounts for multiple scattering [14]. Except in the minimum, the differential cross sections at 142 and 180 MeV (not shown) are fit quite well with the multiple scattering calculations. We note that a preliminary calculation that uses a purely scalar phenomenological ρ^2 term in the optical potential to account for pion absorption [19] predicts A_y completely out of phase with the data at 180 MeV.

Large second-order effects may be caused by the Δ -neutron interaction when the $\Delta(1232)$ resonance dominates the elementary π -nucleon interaction. For this resonance the isospin coupling Clebsch-Gordan coefficients result in much larger scattering amplitudes F and G for π^+ elastic scattering on protons than on neutrons. But the π^+ interacting with the paired-off protons in a $(1s)^3$ ground state of ^3He cannot contribute to the first-order spin-dependent amplitude G which results only from scattering from the unpaired neutron. F has a large (first-order) component from scattering from the two protons and a small one from scattering from the neutron. A large second-order contribution to G arises if the intermediate Δ^{++} , generated with very high probability in π^+ scattering on one of the two protons, interacts with the polarized neutron.

The magnitude of this second-order contribution to G has been investigated by one of us (B. J.) using the simple s -shell model for ^3He with Gaussian single particle wave functions. The rms radius of the nucleon distribution in ^3He was kept fixed at the value $\langle r \rangle^{1/2} = 1.65$ fm obtained by unfolding the finite proton size from the charge density of ^3He [20]. Furthermore, the model employs the PWIA for this second-order term and a meson exchange model for the Δ -neutron interaction which includes the $\pi, \rho, \omega,$ and η mesons. The meson- Δ couplings were obtained from the meson-nucleon couplings by use of SU(6) symmetry and the naive quark model. Two-nucleon correlations were included phenomenologically by multiplying the wave function with a Gaussian correlation function that depends on the relative distance of the interacting particles. The width of the correlation Gaussian was kept fixed at a standard value of 0.75 fm [21]. The resulting second-order term in G was added to the first-order multiple scattering values for F and G .

This hybrid model gives a very good fit to A_y at 180 MeV (dashed line in Fig. 2). The negative A_y near 60° and the shift of the positive maximum towards larger

angles are reproduced. At 142 MeV the magnitude of the negative A_y near 60° is not described as well. At 256 MeV the model including the Δ -neutron interaction is in slightly better agreement with the data than the multiple scattering calculation without the Δ -neutron interaction (solid line). The effect of this interaction on the differential cross section is to fill in the minimum at 142 and 180 MeV, resulting in an improved fit (not shown).

Further theoretical work is needed to determine whether our measured A_y can be explained by some aspect of the reaction mechanism or the ^3He wave function, which we have not yet included. Effects from pion absorption need to be studied further by, for example, including spin and isospin parts in the second-order corrections to the optical potential (ρ^2 term). The Δ -neutron interaction should be treated as part of the full multiple scattering calculations and not simply added on as in this work. At 256 MeV the small components in the ^3He wave function have to be included [15]. No predictions of A_y for ^3He are currently available within the framework of the Δ -hole model. Previous work (reviewed in Ref. [22]) invoked the need of a strong but purely phenomenological Δ -nucleon spin-orbit potential. A microscopic derivation [23] of this term gave a much smaller strength. Nevertheless, its effect on the A_y should be considered in future calculations. Our hybrid model is the first attempt to treat the Δ -nucleon interaction in $\pi^+ ^3\text{He}$ scattering microscopically.

On the experimental side, data for π^- scattering on polarized ^3He are needed. For π^- scattering the first-order contribution to G is much larger than the second-order contribution so that the effect from the Δ -nucleon interaction on A_y is predicted to be negligible.

In conclusion, asymmetries were measured for π^+ elastic scattering from polarized ^3He at energies near the pion-nucleon $\Delta(1232)$ resonance. Thus far conventional pion-nucleus interaction theory has failed to fit the data. However, a large second-order contribution to the spin-dependent scattering amplitude in $\pi^+ ^3\text{He}$ scattering, resulting from the Δ -neutron spin-spin interaction, significantly improves the agreement between experiment and theory.

The authors wish to thank Dr. R. L. Boudrie for his unrelenting support and the technical staff at LAMPF for assistance. This work was supported by the U.S. Department of Energy and the National Science Foundation.

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