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

J. J. Görgen, J. R. Comfort, J. R. Tinsley,(a) T. Averett, J. DeKorse, B. Franklin, and B. G. Ritchie
Physics Department, Arizona State University, Tempe, Arizona 85287

G. Kyle, A. Klein,(b) B. Berman,(c) G. Burleson, and K. Cranston
Physics Department, New Mexico State University, Las Cruces, New Mexico 88003

J. A. Faucett, J. J. Jarmer, J. N. Knudson, S. Penttilä, and N. Tanaka
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

B. Brinkmöller,(d) D. Dehnhard, and Yi-Fen Yen
Physics Department, University of Minnesota, Minneapolis, Minnesota 55455

S. Høibråten
Department of Physics, University of Colorado, Boulder, Colorado 80309

H. Breuer, B. S. Flanders,(e) M. A. Khandaker, D. L. Naples, and D. Zhang
Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742

M. L. Barlett,(f) G. W. Hoffmann, and M. Purcell
Department of Physics, The University of Texas, Austin, Texas 78712
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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.

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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

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

where $\hat{\mathbf{n}}=(\mathbf{k}\times\mathbf{k}')/|\mathbf{k}\times\mathbf{k}'|$ ($\mathbf{k}$ and $\mathbf{k}'$ are the momenta of the incident and outgoing pions), and $\boldsymbol{\sigma}$ is the Pauli spinor 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 protons[1] and polarized nuclei in the $1p$ shell[2] 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)

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

where the arrow indicates the nucleon spin direction relative to $\hat{\mathbf{n}}$ 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 $^{13}\mathrm{C}(\pi^+,\pi^0)$ 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 spectrometer[5] 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 cm^3 of frozen beads, about 1.5 mm in diameter, composed of ethylene glycol OH-$(\mathrm{CH}_2)_2$-OH doped with 7×10^{19} molecules/ml of EHBA-$\mathrm{Cr}^{(\mathrm{V})}$.[6] The carbon was enriched to 99% $^{13}\mathrm{C}$ 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 $\mathrm{mg/cm}^2$. The target cell was cooled to about 0.5 K with a $^3\mathrm{He}$ evaporation refrigerator. A polarization normal to the scattering plane of about 27% was induced by using the dynamic nuclear polarization technique[7] 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 $^{11}\mathrm{C}(\beta)$ 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 $^3\mathrm{He}$ refrigerant. The yield due to non-$^{13}\mathrm{C}$ 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 $^3\mathrm{He}(\pi^+,\pi^0)3p$ 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 $\pi^- p \to \pi^0 n$ reaction.[9] The peak shape had a full width at half maximum of about 5 MeV.

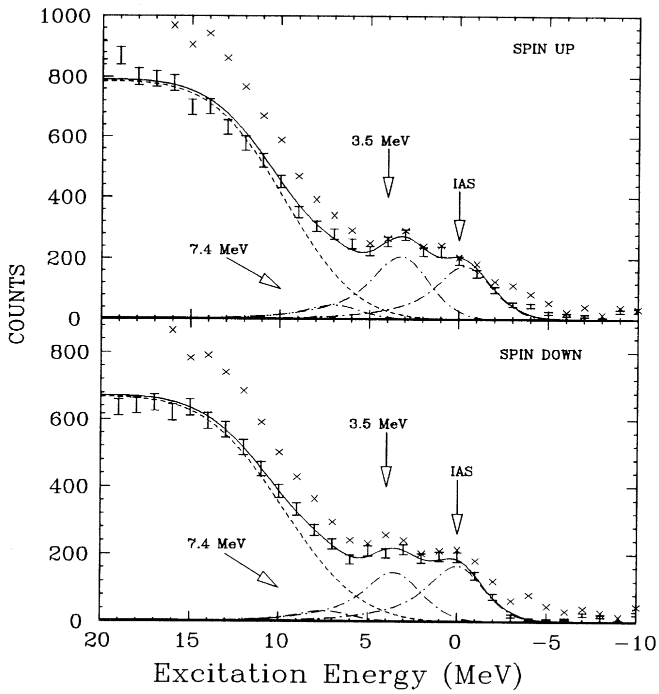

FIG. 1. Spectra for the $^{13}\vec{\mathrm{C}}(\pi^+,\pi^0)$ reaction at 163 MeV and at 22.4°. The solid curve is the fitted sum of three peaks shown individually as dash-dotted curves. The dashed curve represents the fitted nuclear background. The crosses represent the data prior to subtraction of the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

Figure 1 shows spectra for detected events with $X=|E_1-E_2|/(E_1+E_2)\le 0.15$, where E_1 and E_2 are 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 $^{13}\mathrm{C}$. 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 $^{13}\mathrm{C}$. 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 $^{13}\mathrm{N}$ 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

$$A_y(\theta)=(N^+-N^-)/(N^+P^-+N^-P^+)\,, \tag{3}$$

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 $\frac{3}{2}^-$, $\frac{5}{2}^+$ 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 $\frac{3}{2}^-$ 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-

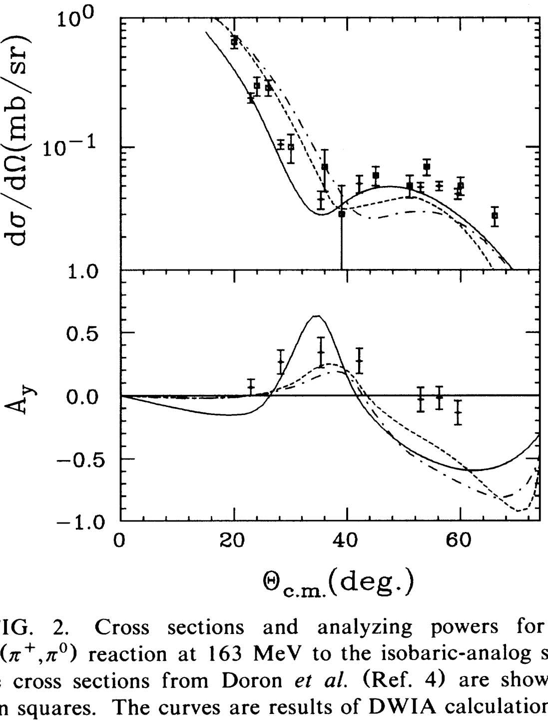

FIG. 2. Cross sections and analyzing powers for the $^{13}\vec{C}(\pi^+,\pi^0)$ reaction at 163 MeV to the isobaric-analog state. The cross sections from Doron *et al.* (Ref. 4) are shown as open squares. The curves are results of DWIA calculations by Siegel (solid), and by Mach (CK wave functions, dashed;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

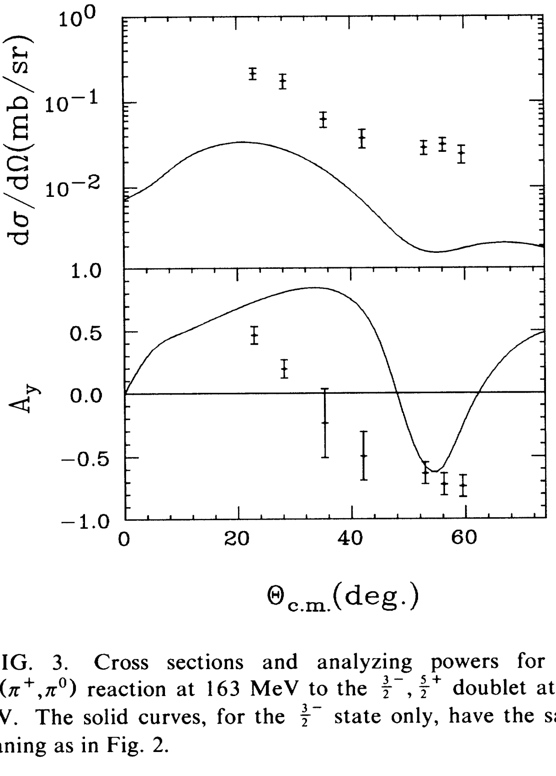

FIG. 3. Cross sections and analyzing powers for the $^{13}\vec{C}(\pi^+,\pi^0)$ reaction at 163 MeV to the $\frac{3}{2}^-$, $\frac{5}{2}^+$ doublet at 3.5 MeV. The solid curves, for the $\frac{3}{2}^-$ state only, have the same meaning as in Fig. 2.

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 functions[14] 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 functions[15] 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.

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[a] Present address: EG&G/EM, 130 Robin Hill Road, Goleta, CA 93116.

[b] Present address: Department of Physics, Old Dominion University, Norfolk, VA 23529.

[c] Present address: Department of Physics, University of New Mexico, Albuquerque, NM 87131.

[d] Present address: Paul Scherrer Institute, CH-5234 Villigen, Switzerland.

[e] Present address: Department of Physics, American University, Washington, DC 20016.

[f] Present address: Applied Research Laboratories, The University of Texas, Austin, TX 78713.

[1] M. E. Sevior *et al.*, Phys. Rev. C **40**, 2780 (1989).

[2] R. Tacik *et al.*, Phys. Rev. Lett. **63**, 1784 (1989).

[3] Y.-F. Yen *et al.*, in Proceedings of Seventh International Conference on Polarization Phenomena in Nuclear Physics, Paris, France, July 1990 (to be published).

[4] A. Doron *et al.*, Phys. Rev. C **26**, 189 (1982).

[5] H. W. Baer *et al.*, Nucl. Instrum. Methods **180**, 445 (1981).

[6] J. J. Jarmer *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **250**, 576 (1986).

[7] A. Abragam and M. Goldman, *Nuclear Magnetism: Order and Disorder* (Clarendon, Oxford, 1982).

[8] B. J. Dropesky *et al.*, Phys. Rev. C **20**, 1844 (1979).

[9] J. J. Görgen *et al.*, Phys. Rev. D **42**, 2374 (1990).

[10] D. Dehnhard *et al.*, Phys. Rev. Lett. **43**, 1091 (1979).

[11] R. J. Peterson, J. R. Shepard, and R. A. Emigh, Phys. Rev. C **24**, 826 (1981).

[12] H. Ohnuma *et al.*, Nucl. Phys. **A456**, 61 (1986).

[13] P. B. Siegel and W. R. Gibbs, in *Proceedings of the LAMPF Workshop on Physics with Polarized Nuclear Targets,* edited by G. Burleson *et al.* (Los Alamos National Laboratory Report No. LA-10550-C, 1986); corrected calculations, P.B. Siegel (private communication); see also P. B. Siegel and W. R. Gibbs, Phys. Rev. C **36**, 2473 (1987).

[14] S. Cohen and D. Kurath, Nucl. Phys. **73**, 1 (1965).

[15] L. Tiator, Phys. Lett. **125B**, 367 (1983).

[16] R. Mach and S. S. Kamalov, Nucl. Phys. **A511**, 601 (1990); R. Mach (private communication).

[17] R. S. Hicks *et al.*, Phys. Rev. C **26**, 339 (1982).