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

Yi-Fen Yen, B. Brinkmöller,[a] D. Dehnhard, S. M. Sterbenz, and Yi-Ju Yu
University of Minnesota, Minneapolis, Minnesota 55455

Brian Berman,[b] G. R. Burleson, K. Cranston, A. Klein,[c] and G. S. Kyle
New Mexico State University, Las Cruces, New Mexico 88003

R. Alarcon, T. Averett, J. R. Comfort, J. J. Görgen, B. G. Ritchie, and J. R. Tinsley[d]
Arizona State University, Tempe, Arizona 85287

M. Barlett, G. W. Hoffmann, K. Johnson, C. F. Moore, M. Purcell, H. Ward, and A. Williams
University of Texas at Austin, Austin, Texas 78712-1081

J. A. Faucett, S. J. Greene, J. J. Jarmer, J. A. McGill,[e] C. L. Morris, S. Penttilä, and N. Tanaka
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

H. T. Fortune, E. Insko, R. Ivie, J. M. O'Donnell, and D. Smith
University of Pennsylvania, Philadelphia, Pennsylvania 19104

M. A. Khandaker
University of Maryland, College Park, Maryland 20742

S. Chakravarti
California State Polytechnic University, Pomona, California 91768
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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.

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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 $^{15}\vec{\mathrm{N}}(\pi^+,\pi^+)$ 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

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

where $\boldsymbol{\sigma}$ is the nuclear Pauli spin matrix, $\hat{\mathbf{n}} = (\mathbf{k}\times\mathbf{k}')/|\mathbf{k}\times\mathbf{k}'|$ 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

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

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 ($^{13}C_4H_{10}O$) 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-^{3}He 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 ^{1}H were measured by a nuclear-magnetic-resonance system. The polarizations were calibrated by measuring the thermal equilibrium[3] 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 small[10] 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

$$A_y = \frac{N_\uparrow - N_\downarrow}{(N_\uparrow - B)P_\downarrow + (N_\downarrow - B)P_\uparrow} = \frac{\mathrm{DIFF}}{\mathrm{SUM}}. \tag{3}$$

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 $\hat{\mathbf{n}}$. $N_\uparrow$ 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 ^{3}He, 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.)

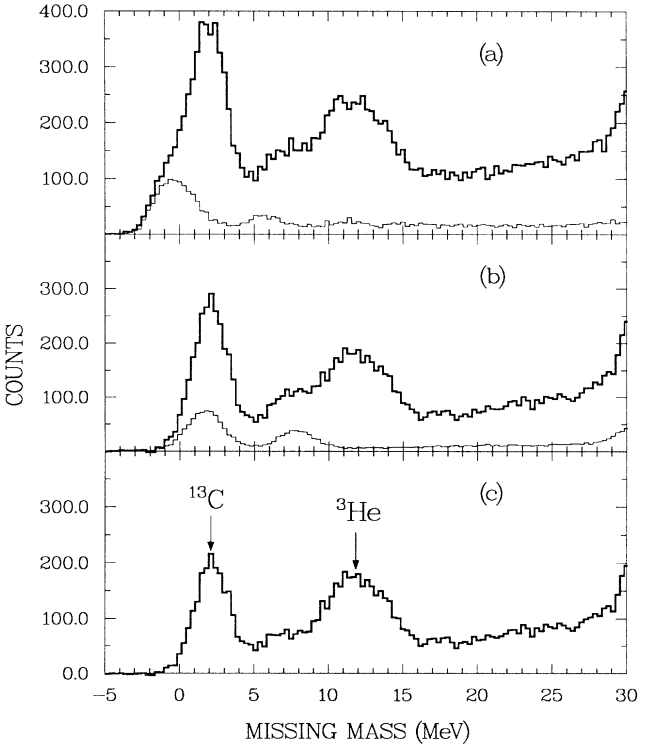

FIG. 1. Typical foreground- and background-subtracted missing-mass spectra for pion scattering from polarized $^{13}C_4H_{10}O$: (a) thick line, full spectrum; thin line, Cu background spectrum; (b) thick line, spectrum with Cu background subtracted; thin line, oxygen background spectrum; (c) thick line, 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 $d\sigma(\theta)/d\Omega$, $\approx 60°$ and $\approx 100°$, 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 experiment[4] 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%.

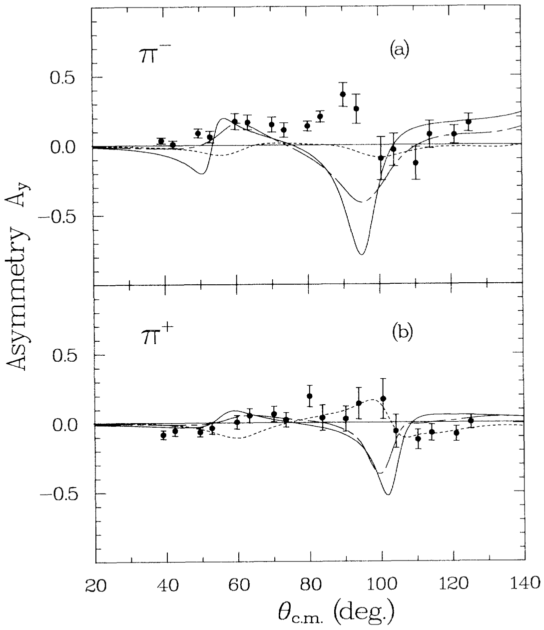

FIG. 2. Asymmetries A_y for elastic scattering of (a) π^- and (b) π^+ from $^{13}\vec{C}$ at $T_\pi = 132$ MeV. The curves are from DWIA calculations of this work (solid lines) and from predictions of Mach (Ref. 6) with densities due to Tiator (Ref. 17) (dashed lines) and with CK (Refs. 14 and 15) densities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

In an attempt to reproduce the data, we have calculated[12] theoretical A_y using a model which employs a first-order optical potential. We used the optical-model program[13] 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 used[10] 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 model[13] 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) model[15] 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 $\approx 100°$), 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

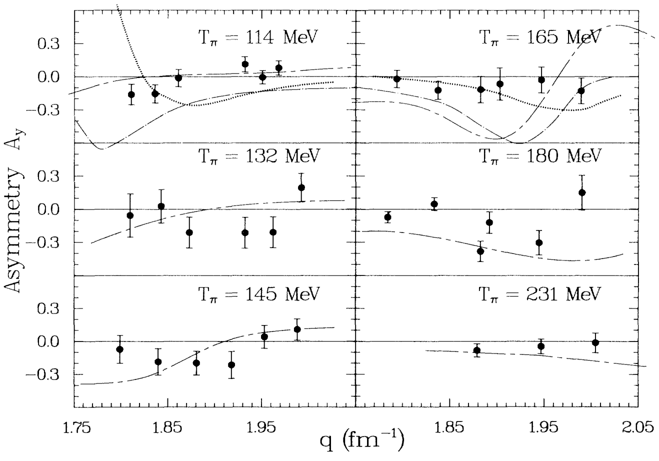

FIG. 3. A_y for elastic scattering of π^- from $^{13}\vec{C}$ at energies across the [3,3] resonance at momentum transfers near the second minimum of the differential cross sections. The curves at 114 and 165 MeV are the predictions of Thies using the Δ-hole model (Ref. 5) (dotted lines) and the closure 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 factor[16] for $q > 1.6$ fm^{-1}.

With the CK densities, Mach[6] 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 densities[17] (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 work[18] on ^{6}Li.

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 coworkers[5] 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.

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[a] Present address: Universität Karlsruhe, D-7500 Karlsruhe, Germany, and Paul Scherrer Institute, CH-5234 Villigen, Switzerland.

[b] Present address: University of New Mexico, Albuquerque, NM 87131.

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

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

[e] Present address: MS 1049, Superconducting Super Collider (SSC) Laboratory, 2550 Beckleymeade Avenue, Dallas, TX 75237.

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