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

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Asymmetries for π^+ elastic scattering from polarized ^{3}He 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]

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In this Letter we report on the first measurement of asymmetries A_y for π^+ elastic scattering from polarized ^{3}He 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 ^{3}He recently became possible with the development of the high-density, optically pumped ^{3}He 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 ^{3}He, 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 ^{3}He show only a slight dependence on the reaction model.

Thus measurements of π^+ elastic scattering from polarized ^{3}He 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 ^{3}He wave function is predicted at $T_\pi \geq 256$ MeV.

The TRIUMF target was set up in the P^{3}E 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 ^{3}He 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 ^{3}He 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-^{3}He collisions to the ^{3}He 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 ^{3}He 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. ^{3}He 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 ^{3}He 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 ^{3}He 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 ^{3}He 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 $\theta_{\rm lab} = 50°$, 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 ↿, the one antiparallel by ⇂. The ^{3}He 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 ^{3}He.

The experimental A_y was obtained using

$$A_y = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}\frac{1}{p}. \tag{1}$$

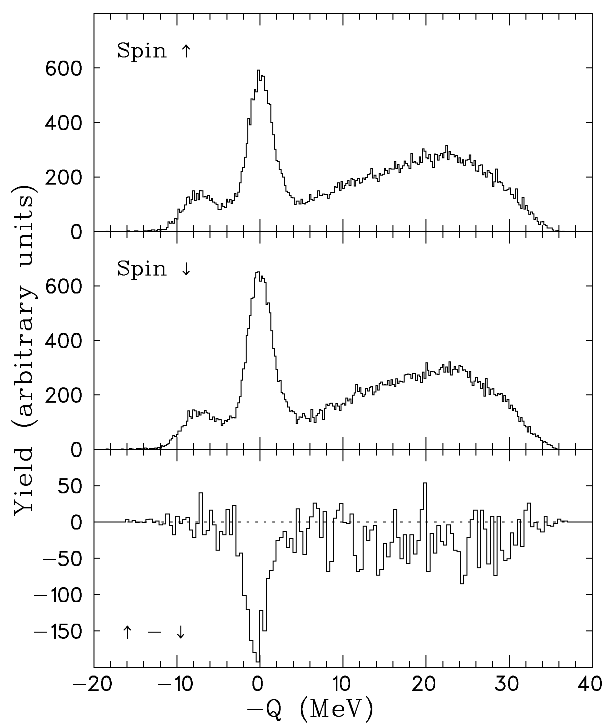

FIG. 1. Typical normalized energy spectra from elastic scattering of π^+ on the polarized ^{3}He target at $T_\pi = 180$ MeV and $\theta_{\rm lab} = 50°$. Top panel: target spin parallel (↿); center panel: target spin antiparallel (⇂) to the normal to the reaction plane. The difference spectrum is shown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

Here $N_\uparrow$ and $N_\downarrow$ are the normalized numbers of counts in the ^{3}He elastic peak with the ^{3}He 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

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

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 ^{3}He 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

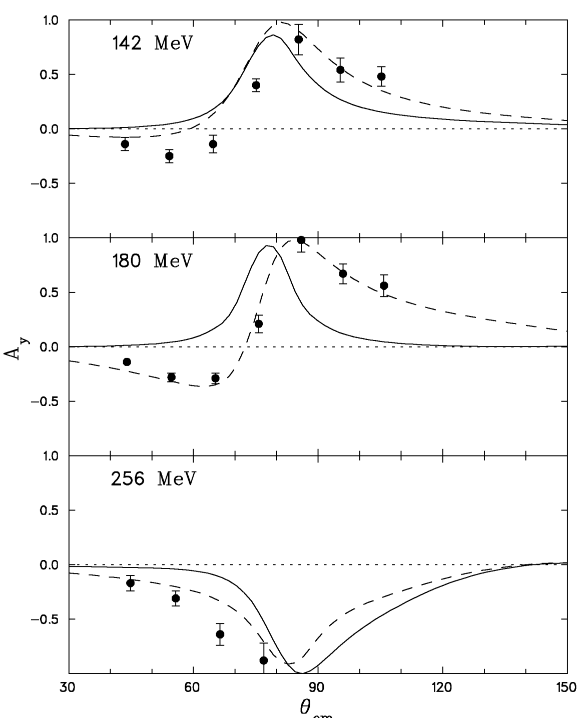

FIG. 2. Asymmetry angular distribution for elastic π^+ scattering from polarized ^{3}He at $T_\pi = 142$ MeV (top), 180 MeV (center), and 256 MeV (bottom). Solid lines: Multiple scattering predictions of Ref. [15] using Faddeev wave functions. Dashed lines: Predictions of the hybrid model (see text).

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 ^{3}He 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 ^{3}He 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 ^{3}He with Gaussian single particle wave functions. The rms radius of the nucleon distribution in ^{3}He 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 ^{3}He [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 π, ρ, ω, 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 ^{3}He 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 ^{3}He wave function have to be included [15]. No predictions of A_y for ^{3}He 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-nucleus 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 π^+ ^{3}He scattering microscopically.

On the experimental side, data for π^- scattering on polarized ^{3}He 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 ^{3}He 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 π^+-^{3}He scattering, resulting from the Δ-neutron spin-spin interaction, significantly improves the agreement between experiment and theory.

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