Spin Effects in π-Nucleus Scattering in the Region of the $\Delta(3,3)$ Resonance

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We present the first measurements of spin effects in π^+ elastic and inelastic scattering from complex nuclei, $^{15}\vec{N}(\frac{1}{2}^-)$ and $^{6}\vec{Li}(1^+)$. For the case of $^{15}\vec{N}$, the analyzing power A_y was measured at $T_\pi = 164$ MeV between 60° and 100°. Although large values of A_y are predicted by theory, the data are consistent with zero. For the case of $^{6}\vec{Li}$, the analyzing power iT_{11} was measured at $T_\pi = 134$ and 164 MeV, between 50° and 110°. Large values of iT_{11} were found at some angles, but the measured angular distributions differ considerably from theoretical predictions.

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There have been several past instances in which investigations of spin effects in experiments with strongly interacting particles have led to a reconsideration of underlying reaction dynamics. In the case of nucleon-nucleus scattering, for example, polarization studies have revealed that the natural framework for calculations is provided by the Dirac equation.[1] Another example is that of high-energy proton-proton scattering, where there are difficulties in interpreting spin observables in terms of perturbative QCD, while spin-averaged data are described correctly.[2] Thus it is not surprising that with the availability of polarized targets in recent years, there has been a growing interest in their use with pion beams.

The general expression for the analyzing power A_y for pion scattering from a $J=\frac{1}{2}$ nucleus is given by $A_y = [2/\sigma(\theta)]\mathrm{Im}[f(\theta)g^*(\theta)]$, where σ is the spin-averaged cross section $\sigma(\theta) = |f(\theta)|^2 + |g(\theta)|^2$, and f and g are the pion-nucleus non-spin-flip and spin-flip amplitudes. To date, only cross-section data have been available. It is clear that A_y is much more sensitive than σ to the weaker spin-flip amplitude, and to the relative phase between f and g. Thus, measurements of polarization observables will provide new information which should lead to a better understanding of the pion-nucleus interaction.

A workshop on physics with polarized nuclear targets at LAMPF in 1986[3] stimulated several experimental proposals, and number of theoretical studies. Polarization observables have been calculated for pion elastic and inelastic scattering from ^{6}Li,[4-7] ^{13}C,[8-10] ^{14}N, and ^{15}N.[11] The results of the various calculations differ widely from each other, but large polarization effects are generally predicted close to the minima in $d\sigma/d\Omega$.

The first proposal to study pion scattering from polarized nuclei dates back to 1980,[12] when Horikawa, Thies, and Lenz[13] introduced a Δ-nucleus spin-orbit interaction into the Δ-hole model. Its purpose was to eliminate the previously observed energy dependence of the Δ spreading potential, and to improve the description of $d\sigma/d\Omega$. Although this *ad hoc* inclusion of a spin-orbit term was plausible, there was no basic justification for the particular form or strength chosen. Recent calculations by Ernst and Dhuga[14] indicate a much weaker spin-orbit interaction, while Freedman, Miller, and Henley[15] have obtained fits to elastic-cross-section data without any such term. Pion scattering from complex nuclei may provide some insights into this question. Such experiments might also provide information on the more microscopic Δ-nucleon interaction. There has been a considerable theoretical effort recently[7,16,17] to isolate the isospin-flip and isospin-nonflip contributions to the ΔN interaction from measured isospin ratios in $(\pi,\pi p)$ reactions,[18] and (π,π') reactions involving $\Delta T=1$ transitions.[19] In this context, Thies[20] has pointed out that due to the symmetry between spin and isospin in the effective ΔN interaction one may also be able to separate the spin-flip and non-spin-flip parts of the ΔN interaction from measurements of spin observables in pion-nucleus scattering. This would tie in to the analysis[21] of recent measurements of iT_{11} in $\pi\vec{d}$ elastic scattering,[22] which indicated the existence of a strong spin-spin term in the ΔN interaction.

As the first step in a systematic program, we have investigated π^+ scattering from $^{15}\vec{\mathrm{N}}$ at 164 MeV and $^6\vec{\mathrm{Li}}$ at 134 and 164 MeV, in the angular range between 50° and 110°. The experiment was performed with the πM1 beam, the SUSI magnetic spectrometer, and the polarized target setup[22] at the Paul Scherrer Institute (formerly SIN) in Switzerland. The $^{15}NH_3$ target material was prepared at the University of Bonn, and the ^{6}LiD at Saclay. The processes involved in the target preparation are described in Refs. 23 and 24. The target materials were polarized by microwave irradiation in a magnetic field of 2.5 T. The target polarizations were determined by comparing the dynamically enhanced ^{15}N and ^{6}Li NMR signals with the thermal equilibrium signals. Typical values of $p_z=\pm 0.17$ and ± 0.35 were obtained for $^{15}\vec{\mathrm{N}}$ and $^6\vec{\mathrm{Li}}$, respectively. Typical polarizing times (for reaching 90% of the maximum values) were 12 h for ^{15}N and 8 h for ^{6}Li. Because of these relatively long polarizing times, the data-taking procedure was different from that employed in our earlier experiments:[22] Instead of reversing the polarity of the target several times while holding the spectrometer angle fixed, the entire angular distribution was measured before the sign of the target polarization was reversed. The background from pion scattering from the walls of the target cells and the helium coolant was measured in separate runs.

Scattering yields were determined by fitting the peaks in the energy-loss spectra after the background was subtracted. As a consistency check, the relative differential cross sections for $\pi\,^4$He scattering were extracted and good agreement was found with previously published results.[25] The same was true for the unpolarized πp (Ref. 26), πd (Ref. 27), and $\pi\,^{15}$N (Ref. 28) differential cross sections. Typical background-subtracted spectra are shown in Fig. 1. The spectra have been normalized to equal numbers of incident pions. Note that the relatively large widths of the πp and πd peaks are due to kinematical broadening over the 9° SUSI acceptance. In the $^{15}NH_3$ spectrum, there is a large difference in the yields for positive and negative polarization for $\pi\vec{p}$ scattering as expected from the well-known phase shifts in this energy region, but very little difference for $\pi\,^{15}\vec{\mathrm{N}}$ scattering. In the ^{6}LiD spectrum, there are sizable differences in the yields for positive and negative polarization for $\pi\,^6\vec{\mathrm{Li}}$ elastic and inelastic scattering, as well as for $\pi\vec{d}$.

For the spin-$\frac{1}{2}$ nucleus ^{15}N, the analyzing power A_y was calculated from the measured cross sections σ^+ and

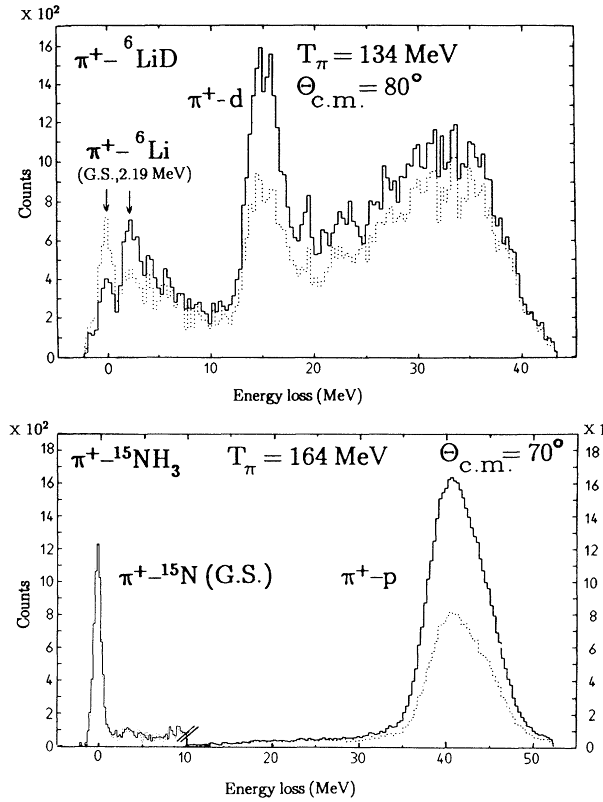

FIG. 1. Typical energy-loss spectra for π^+ scattering from ^{6}LiD and $^{15}NH_3$. The solid lines correspond to positive, and the dotted lines to negative target polarization.

σ^- and the corresponding target polarizations p_z^+ and p_z^- according to

$$A_y=\frac{\sigma^+-\sigma^-}{\sigma^+p_z^-+\sigma^-p_z^+},$$

where the superscript $+$ $(-)$ for p_z indicates the direction parallel (antiparallel) to the quantization axis of the polarized target, defined as $\mathbf{n}=\mathbf{k}\times\mathbf{k}'$, with $\mathbf{k}$ the momentum of the incident pion, and $\mathbf{k}'$ the momentum of the scattered pion.

For the spin-1 nucleon ^{6}Li, the vector analyzing power iT_{11} was calculated from the measured cross sections σ^+, σ^-, and σ^0 (for positive, negative, and zero target polarizations) and the target vector (p_z) and tensor (p_{zz}) polarizations according to

$$iT_{11}=\frac{p_{zz}^-(\sigma^+-\sigma^0)-p_{zz}^+(\sigma^--\sigma^0)}{\sqrt{3}(p_{zz}^-p_z^++p_{zz}^+p_z^-)\sigma^0}.$$

The target vector and tensor polarizations are related by $p_{zz}=2-(4-3p_z^2)^{1/2}$.

The error bars shown in Figs. 2 and 3 include the statistical uncertainties in the determination of σ^+, σ^-, and σ^0, as well as the uncertainties arising from background subtraction. The uncertainty in the value of the

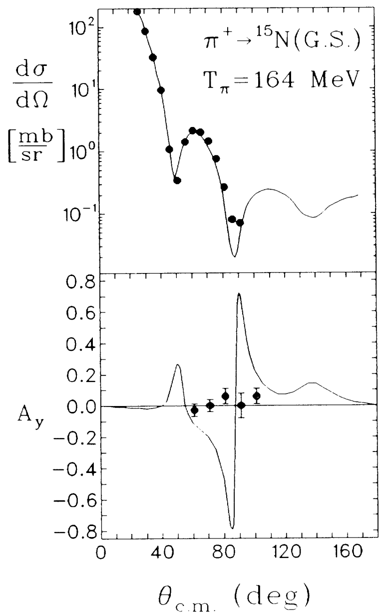

FIG. 2. The analyzing power A_y (present experiment) and $d\sigma/d\Omega$ (Ref. 28) for π^+- ^{15}N scattering compared with predictions from R. Mach.

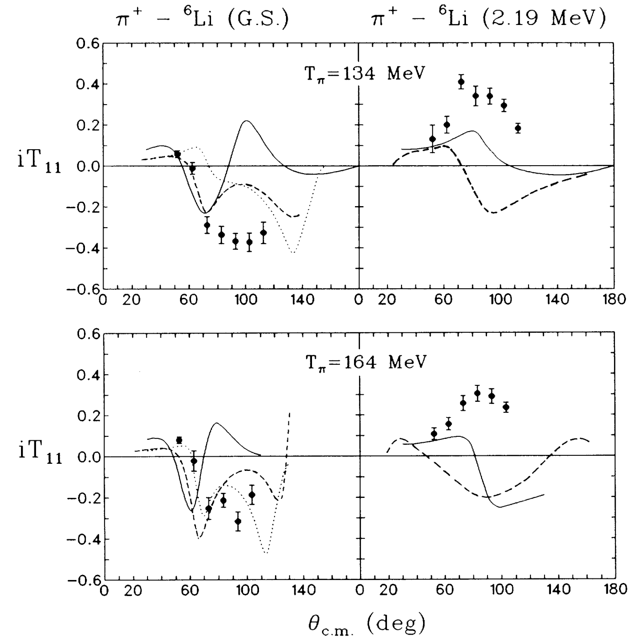

FIG. 3. The analyzing power iT_{11} for π^+ scattering from the ground state (G.S.) and the first excited state (2.19 MeV) of $^6\vec{Li}$. The data are from the present experiment; the solid and dotted lines are the theoretical predictions from R. Mach using shell-model and cluster-model wave functions, respectively. The dashed lines are the predictions from K. Junker using a semiempirical wave function which contains cluster properties (see text).

target polarization (10%) enters only as an overall normalization factor and has not been included.

The present results for A_y for $^{15}\vec{N}$, along with the measured $d\sigma/d\Omega$ from Ref. 28 are compared with theoretical predictions from R. Mach in Fig. 2. The calculations are based on the momentum-space coupled-channel formalism of Gmitro, Kamalov, and Mach,[29] using a shell-model wave function [pure $p_{1/2}$ hole normalized to (e,e') data], which is very similar to the one used by Riesenfeld *et al.*[30] in their study of electron production of pions. The comparison is quite surprising: The calculations reproduce $d\sigma/d\Omega$ very well; however, the large values of A_y predicted to occur near the minima in $d\sigma/d\Omega$ are not observed. In fact, the measured values of A_y are consistent with zero. This was also the case when the data were analyzed with the angular acceptance of the SUSI spectrometer divided into two parts, in order to verify that there was no rapid angular variation of A_y which was being averaged. At present it is not clear whether the serious discrepancy between the data and the theoretical predictions is due to inadequacies in the nuclear structure input to the calculation, or to some missing reaction dynamics. It may be interesting to note that a quenching of spin matrix elements has been observed in (e,e'), (p,p'), and (p,n) reactions, and that Δ excitations are believed to be one of the principal contributors to this quenching phenomenon.[31]

The experimental data for iT_{11} for ^{6}Li are compared with theoretical predictions in Fig. 3. The solid and dotted lines represent the calculations of R. Mach (R.M.), using shell-model and cluster-model wave functions, respectively (see Ref. 6). The dashed lines represent the calculation of K. Junker (K.J.). They are based on the Δ-hole model using shell-model wave functions with different well parameters for the s- and p-shell nucleons. The empirical wave function of Ref. 32 has been used for the p-shell nucleons. The nucleon density[33] entering the Δ-hole calculation is therefore very similar to a cluster-model density. This may explain the similarity of K.J.'s predictions to those of R.M. using cluster-model wave functions. The measured values of iT_{11} are sizable for both elastic and inelastic scattering to the 3^+ state, but there are substantial differences between the data and the theoretical predictions. The calculated values appear to be quite sensitive to the nuclear-structure model used. Differential cross sections have not been measured at our energies, but data do exist[34] at 100, 180, and 240 MeV, and are reasonably well reproduced by the calculations.

The serious discrepancies between the measured and calculated polarization observables call for further experimental and theoretical studies. These are now in progress. The study of spin effects may open a new chapter in pion-nucleus physics.

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