Analyzing Powers in π^+p Elastic Scattering at Intermediate Energies

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The analyzing power, A_N, has been measured for π^+p elastic scattering at $p_\pi = 471$, 547, 625, and 687 MeV/c on a transversely polarized target. The results are compared with three recent partial-wave analyses for the isospin-$\frac{3}{2}$ channel. The agreement with our data for all three analyses is good at 471 MeV/c and reasonable at 547 and 625 MeV/c. At 687 MeV/c two of the analyses show a sharp maximum near $\cos\theta = -0.4$ which is not seen in the data. There is no indication in our data of the existence of new, narrow Δ resonances.

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We report here on precise measurements of the analyzing power, A_N, in π^+p elastic scattering at momenta between 471 and 687 MeV/c (invariant mass between 1350 and 1490 MeV/c^2). This experiment is part of our program to obtain a complete set of $\pi^\pm p$ elastic scattering and charge-exchange data in this momentum region. Our differential-cross-section data for elastic scattering at the same momenta have previously been reported.[1]

In addition to the basic need for accurate data in the π^+p system to determine the isospin-$\frac{3}{2}$ amplitudes, these measurements will contribute to progress on a variety of issues of current interest. A search for new low-mass Δ resonances provides a test of the Karl-Isgur-Koniuk (KIK) quark model with one-gluon exchange.[2] The KIK quark model has no room for the $P_{31}(1550)$, a one-star candidate[3] seen in pion photoproduction and in $\pi N \to \pi\pi N$. There is also a two-star P_{33} candidate[3] with a mass of either 1522 MeV (Karlsruhe-Helsinki) or 1600 MeV (Carnegie-Mellon University–Lawrence Berkeley Laboratory); the KIK quark model predicts a P_{33} with a mass of about 1780 MeV. Precise isospin-$\frac{3}{2}$ πN amplitudes will be useful in constructing improved nucleon-nucleon potentials, such as the Paris potential, for nuclear physics.[4] Accurate experimental values are needed to test specific predictions of recent πN partial-wave calculations in the Skyrme-soliton model[5–7] and in the π-Δ coupling model.[8] This last work is particularly interesting because of the assertion that excellent fits to various phase shifts and inelasticities are possible without the need for well-established resonances such as the Roper $N(1470)$, the $\Delta(1620)$, and others. Recently, a claim was made[9] for the discovery of a new, very narrow dibaryon state with a mass of 2.24 GeV and a width of 16 MeV. Such a narrow state, if it really exists, would imply a new and complicated structure of the πN interaction which is believed to govern the NN interaction. It is imperative to establish that no narrow πN resonances were overlooked in older experiments.

The issues mentioned above can only be satisfactorily addressed by determination of unique πN partial waves. This requires the measurement at each angle and energy of four independent observables, such as the differential cross section, $d\sigma/d\Omega$, the analyzing power, A_N, and the Wolfenstein spin-rotation parameters, A and R. As no measurement has yet been made of A and R below 6 GeV, the ambiguities introduced by the use of an incomplete data set must be remedied in a πN partial-wave analysis (PWA) with the aid of theoretical constraints. These constraints typically include unitarity, analyticity (via dispersion relations), and isospin invariance. Various groups have obtained πN scattering amplitudes by fitting the available data on cross sections and analyzing powers for πp elastic scattering and the charge-exchange reaction with varying use of analytical constraints. There are available three recent partial-wave analyses by Hohler *et al.*[10] and Koch and Pietarinen[10] (K-H), by Cutkosky *et al.*[11] (C-L), and by Zidell *et al.*[12] (VPI). The differences among these three analyses are in the degree to which theoretical constraints are applied and in the experimental data used. In particular, the K-H and C-L analyses make extensive use of constraints, particularly dispersion relations, to constrain the high partial waves, while the VPI analysis relies more heavily on experimental input. New data, especially for A_N, which are not as plentiful as differential-cross-section measurements, enable us to investigate the reliability of these analyses.

The experiment was performed at the Clinton P. Anderson Meson Physics Facility (LAMPF) with the P^3 channel. The layout of the experimental setup is shown in Fig. 1. The apparatus and measurements are described in detail elsewhere.[13] Values for A_N were determined over a wide range of scattering angles

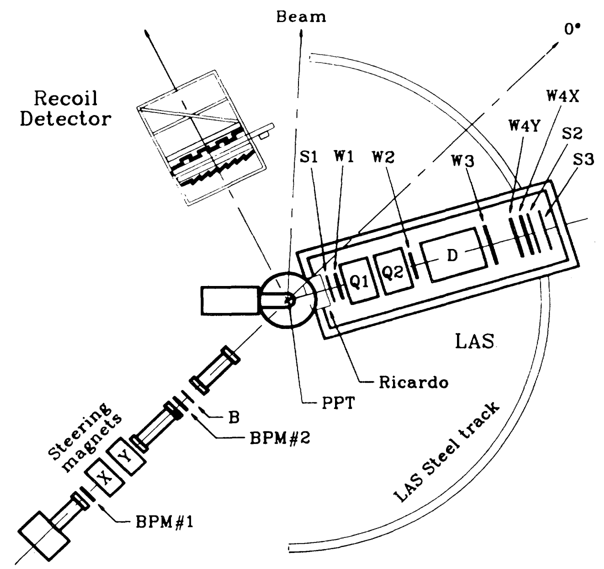

FIG. 1. Layout of the experimental setup. BPM-1 and BPM-2 are the beam profile monitors. B is the beam counter. S1–S3 represent the LAS entrance and exit scintillation counters. W1–W4 are the multiwire proportional chambers. The LAS quadrupoles are marked Q1 and Q2 and D is the bending magnet dipole. Also shown are the polarized proton target (PPT) and the Ricardo steering magnet.

($0.5 \geqslant \cos\theta_{\text{c.m.}} \geqslant -0.9$, typically) at incident π^+ momenta of 471, 547, 625, and 687 MeV/c by measurement of elastic scattering from a transversely polarized proton target (PPT). The target consisted, of 1,2-propanediol beads contained in a cylindrical target cell 2 cm in diameter and 4 cm long, with the pion beam incident along the cylinder axis. The target was dynamically polarized in a 2.5-T magnetic field; reversal of the polarization was accomplished by the appropriate shift in the frequency of the microwaves used for dynamic polarization. The target polarization, which was typically 80%, was measured with the use of an integrating NMR system that was read every 3–5 min during data taking. The absolute calibration of the NMR system was accomplished by periodic measurements of the thermal-equilibrium polarization signal at 1 K. The uncertainty in these measurements of the thermal-equilibrium NMR signal gives rise to a 3% systematic uncertainty in the polarization.

The transverse spot size and location of the beam at the target position was established by exposure of film placed just downstream of the target; the beam was centered on the target by means of x- and y-plane steering magnets in the beam line 5 m upstream of the target as shown in Fig. 1. A pair of wire chambers in the beam upstream of the target was used to monitor possible beam drift during the experiment. The beam flux was typically 10^6 π^+/sec in a 2-cm-diam spot on target. The incident beam central momenta and momentum bites (FWHM) were 471(10), 547(6), 625(8), and 687(32) MeV/c. The central momentum of the beam is known to $\pm 0.3\%$.[14,15]

The scattered pions in all but five cases were detected in the LAMPF large-acceptance spectrometer[16] (LAS) in coincidence with the protons, which were detected in the recoil arm. In these five cases the protons were detected in LAS and the pions in the recoil arm. LAS is a vertically bending quadrupole-quadrupole-dipole spectrometer, and thus the measurements of the scattering angle and momentum are not correlated. The field of the PPT magnet produced a substantial horizontal bending of the trajectory of the incident and final-state charged particles; as examples, the bend angle of the 471-MeV/c incident beam was 18° and for 250-MeV/c recoil protons it was 35°. Because the pivot of LAS was centered on the target, the deflection of the scattered pions in the field of the PPT caused a significant reduction in the acceptance of LAS. To compensate for this a dipole magnet was installed at the entrance of LAS (Ricardo in Fig. 1). It was located in the large fringing field of the PPT magnet and it was attached to and rotated with LAS. Position information in both the x and the y plane from each of four wire chambers, two upstream of the spectrometer bending magnet and two downstream, was used to determine the apparent pion scattering angle and momentum. Particle species were identified by time of flight (TOF) and pulse height in three sets of LAS scintillators.

The recoil detector consisted of a wire chamber with an active area 100 cm (x plane) by 65 cm (y plane) placed between two scintillator hodoscopes. The position data from the wire chamber, the pulse heights in the scintillators, and the TOF relative to the LAS scintillators were measured for each particle.

The highly overconstrained signal derived from this detection system resulted in excellent background suppression; the signal-to-background ratio was typically 7:1 even though the target contained only 7% free hydrogen and the beam-interaction rate in the walls of the target cell and cryostat was substantial. The background yields were measured in separate runs in which the propanediol sample was replaced by graphite beads having the same density as the carbon component of the propanediol.

For each accepted event we recorded the pulse height in all struck scintillators, the TOF through LAS, the recoil-proton TOF, and the position data from all wire chambers. In the off-line analysis, the LAS wire-chamber data were used to obtain the pion trajectories in the horizontal and vertical planes, the pion momentum, and the apparent interaction point in the target and to reject muons from pion decay in the spectrometer. ("Apparent interaction point" implies that no compensation was made for energy loss in the target or for bending of the particles in the PPT magnetic field). Each data run was replayed in several passes in which cuts were applied to increasing numbers of parameters in the following order: LAS TOF, LAS scintillator pulse height, recoil TOF and scintillator pulse height, the apparent target-interaction point, and the muon rejection angles in the horizontal and vertical planes after the bend in LAS. Following each pass the analyzing power was calculated after background subtraction, and we tested that the values obtained were mutually consistent. The background data were, of course, subjected to parameter cuts identical to those used for the hydrogen-signal runs in each case.

The pion scattering angle for each accepted event was calculated from the measured momentum in LAS; this avoids uncertainties connected with the bending of particles in the field of the PPT. The scattering at most angular settings was large enough to allow the 9° angular acceptance of LAS to be divided into two or more bins.

Our results for the analyzing power, A_N, are presented in Figs. 2(a)–2(d); only statistical errors are indicated. The systematic error is $\pm 3\%$ due to the uncertainty in the absolute calibration of the target polarization. Also shown are the results of the partial-wave analyses by the K-H,[10] C-L,[11] and VPI [12] groups; none of these analyses include the present data. The general features of the angular distributions for A_N do not vary greatly from 471 to 625 MeV/c except that the magnitude of A_N at $\cos\theta = -0.4$ increases from -0.2 to -0.8. There is a dramatic change, however, in A_N between 625 and 687 MeV/c, illustrating the great sensitivity of the analyzing power to the energy dependence of certain partial waves. It is imperative for a high-quality measurement of A_N in our energy region that the beam momentum calibration is correct and that the spread in beam momentum is small and well known. At $p_\pi = 471$ MeV/c the agreement of the results of all three analyses with our data is good. At 547 and 625 MeV/c all analyses generally reproduce the shape of the angular distributions, although at forward angles the agreement is a little better for the VPI analysis than for the other two analyses, and at 547 MeV/c at $\cos\theta = -0.5$ and -0.7 the PWA's fall somewhat below our data. Finally, at $p_\pi = 687$ MeV/c, the analyses by the K-H and VPI groups predict a large maximum in A_N near $\cos\theta = -0.4$ which is not seen in our experiment. We can summarize our results as follows: The results of all three recent partial-wave analyses are in acceptable agreement with our A_N data up to 625 MeV/c, suggesting that our measurements, together with our cross-section measurements at these and other beam momenta, present no evidence for new Δ resonances with mass less than 1450 MeV/c^2. New partial-wave analyses that incorporate our data are needed before any conclusions may be drawn concerning the possibility of higher-mass resonances and before comparisons may be made with the predictions of the Skyrme-soliton and π-Δ coupling models.

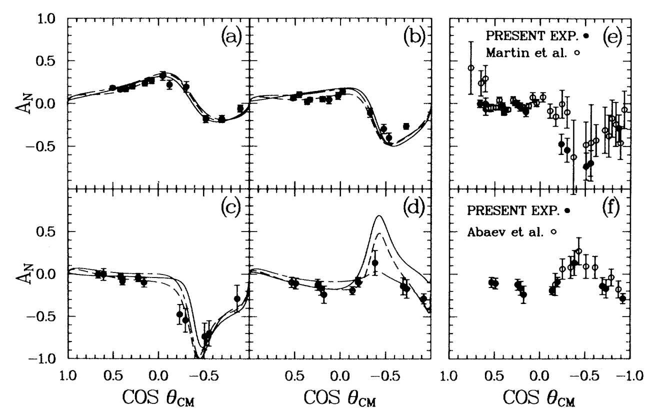

FIG. 2. (a)–(d): Analyzing power, A_N, measured in $\pi^+ p$ elastic scattering with use of transversely polarized target. The incident pion momenta are 471, 547, 625, and 687 MeV/c, respectively. The curves are the results of the three partial-wave analyses of Ref. 10 (solid curve), Ref. 11 (dot-dashed curve), and Ref. 12 (dashed curve). (e) Results of the present experiment at 625 MeV/c compared to the data of Martin *et al.* (Ref. 17) at 617 MeV/c. (f) Results of the present experiment at 687 MeV/c compared to the data of Abaev *et al.* (Ref. 18) at 685.5 MeV/c.

There are two experiments on A_N in $\pi^+ p$ elastic scattering at momenta near the upper end of the range of the present measurements. The experiment by Martin *et al.*[17] covers many incident pion momenta, including 603, 617, 660, 674, and 708 MeV/c, and many scattering angles, but the uncertainties at backward angles are typically ± 0.3 and often larger; this limits the usefulness of these results. A comparison of the Martin *et al.* results with our data at the beam energy closest to ours is shown in Fig. 2(e). The measurements by Abaev *et al.*[18] at $p_\pi = 455$ to 705 MeV/c are restricted to scattering angles larger than 100° with typical uncertainties of ± 0.1. In Fig. 2(f) we compare the Abaev *et al.*, data to ours at the nearest beam momentum. The measurements of Martin *et al.* and of Abaev *et al.* are not in conflict with our more precise data.

Using the VPI SAID program we added our data to the existing data base for a single-energy PWA. The effect on the various phases is small indicating that the isospin-$\frac{3}{2}$ πN amplitudes in our energy region are reasonably well understood.

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