RAPID COMMUNICATIONS

PHYSICAL REVIEW D VOLUME 33, NUMBER 1 1 JANUARY 1986

Rapid Communications

Analyzing power for $\pi^- p$ elastic scattering in the energy region of the Roper resonance

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(Received 28 May 1985)

High-precision measurements of the analyzing power A_N in $\pi^- p$ elastic scattering at $p_\pi = 471$–687 MeV/c are presented and compared with the results of recent πN partial-wave analyses (PWA's) by the Karlsruhe-Helsinki, CMU-LBL, and VPI groups. While agreeing with the main features of the measured angular dependence of A_N, the three PWA's yield larger values than the measurements at forward angles at $p_\pi = 471$, 547, and 625 MeV/c. At 687 MeV/c the PWA's do not agree with the data at far backward angles. We estimate the effect of our data on the phase shifts in this energy region, which includes the Roper resonance.

Since its discovery in an early partial-wave analysis,[1] the $N(1440)$ P_{11} πN resonance, the "Roper resonance," has been an enigma. The four-star rating by the Particle Data Group[2] notwithstanding, there is uncertainty over the properties of the Roper resonance, and the controversy regarding its nature and quark-model classification continues. The partial-wave analyses (PWA's) do not concur on mass M, width Γ, or inelasticity η. The Karlsruhe-Helsinki[3] (KH) collaboration reports $M = 1410 \pm 12$ MeV, $\Gamma = 135 \pm 10$ MeV, and $\eta = 0.49 \pm 0.05$, while the Carnegie Mellon University–Lawrence Berkeley Laboratory[4] (CMU-LBL) collaboration quotes $M = 1440 \pm 30$ MeV, $\Gamma = 340 \pm 70$ MeV, and $\eta = 0.32 \pm 0.04$. The controversy over the width is exacerbated by the possibility that there could be two closely spaced P_{11} resonances. Ayed[5] first proposed a split of the Roper resonance based on the Saclay PWA; he found masses of 1413 and 1532 MeV. Although this proposed split is not confirmed by the KH or CMU-LBL analyses, a new PWA by the Virginia Polytechnic Institute and State University (VPI) group,[6] which parametrizes the resonances in terms of poles in the complex energy plane rather than using the more familiar Breit-Wigner parametrization, shows two P_{11} poles at $P_1 = (1359 - 100i)$ MeV and $P_2 = (1410 - 80i)$ MeV.

There are many quark models that predict the spectra of baryons, notably bag models, potential models, and flux-tube models.[7-12] More recently, explicit calculations of phase shifts have been made in the context of the Skyrme soliton model.[13,14] Finally, it has been pointed out that some resonances seen in πN scattering, including the Roper resonance, may be attributed to the opening of the threshold for the production of the $\Delta(1232)$.[15] The ultimate test of these models is a comparison with the experimentally determined spectra of baryon resonances. The existence and properties of the resonances are deduced from partial-wave analyses of πN elastic-scattering data.

We mention briefly here the predictions of a variety of theoretical models for P_{11} resonances in the energy region of the Roper resonance, in order to illustrate the diversity of theoretical treatments of the baryons.

(a) Quark models. On the basis of the cloudy bag model, Umland *et al.*[7] predict a P_{11} doublet with masses of 1418 and 1533 MeV. Bowler and Hey[8] stress the importance of direct gluon-exchange contributions in the framework of the MIT bag model. They predict radially excited N^* states at 1543 and 1646 MeV. Degrand and Rebbi[9] add a surface oscillation term to the bag model and obtain P_{11} states at 1410 and 1603 MeV. Close and Horgan[10] extend the Bowler-Hey model by including another exchange amplitude and the breathing mode excitations of DeGrand and Rebbi and obtain P_{11} masses of 1416 and 1617 MeV. Recently, a hybrid type of hadronic matter containing both constituent quarks and gluons has been proposed.[11,12] The lowest-mass hybrid-baryon candidate is a P_{11} state with a mass near 1400 MeV. It is interesting to speculate that the reported splitting[5,6] of the Roper resonance might be related to the existence of this hybrid P_{11} in addition to the ordinary three-quark P_{11} resonance.

(b) Skyrme soliton models. Recently, Hayashi *et al.*[13] have made explicit calculations of phase shifts in the context of the Skyrme soliton model. Using the experimental value of η in the P_{11} channel they find that the resonance should occur 50–100 MeV below the Roper resonance. Breit and Nappi[14] have studied the simplest vibrational excitation of

the Skyrmion, the breathing mode. They identify the Roper resonance with a nucleon breathing mode at 1270 MeV.

(c) π-Δ coupling model. In a completely different spirit, Blankleider and Walker[15] have investigated the possibility that some low-lying resonances seen in πN elastic scattering may be due to the opening of the threshold for π-Δ production; they have obtained excellent fits to the P_{11} and other resonance phase shifts and inelasticities without the need for introducing the Roper and other well-established resonances explicitly.

It is clear that the values obtained for the parameters of the Roper resonance by various analyses are in conflict. A precise and unambiguous determination of the scattering amplitudes in this energy region may help test the results of a number of theoretical models. As our information on the resonance parameters comes exclusively from partial-wave analyses, it is important to test the validity of the recent PWA's by a comparison with data on the analyzing power in $\pi^{\pm} p$ elastic scattering.

In this paper we report on the measurements of the analyzing power A_N in $\pi^- p$ elastic scattering. The experiment was carried out in the pion-particle-physics (P^3) channel at the Clinton P. Anderson Meson Physics Facility (LAMPF). Data were obtained at 471, 547, 625, and 687 MeV/c. The incident-beam intensity varied from 0.2 to 4×10^6 π^-/sec. The transverse spot size of the beam at the target was 2×2 cm. The central beam momentum is known to $\pm 0.3\%$.[16,17] The central beam momentum in MeV/c and, in parentheses, the channel momentum bite in percent in each case are 470.8 (2.0), 546.9 (1.3), 624.9 (1.6), and 687.0 (5.3). A relative measurement of the beam intensity was made using scintillator telescopes which detected muons from the decay of pions in the beam.

The experimental setup included a transversely polarized proton target. The polarized target magnet produced a uniform field of 2.5 T over the target volume. The target material consisted of 1,2-propanediol beads in a cylindrical cell 2 cm in diameter and 4 cm long, with the pion beam incident along the axis of the cylinder. High polarization was obtained using a microwave pumping technique. The target was maintained at an average polarization of 80% throughout the experiment. Standard NMR techniques were used to monitor and measure the target polarization. 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.

Details of the experimental setup are given in Refs. 18 and 19. Briefly, the scattered pion and the recoil proton were detected in coincidence (except at $p_\pi = 547$ MeV/c, $\theta_{\text{c.m.}} = 120°$ where only the pion was detected) using the LAMPF large-acceptance spectrometer[20] (LAS) and a recoil detector. The recoil detector consisted of a 100 by 65 cm wire chamber sandwiched between two arrays of eight scintillation counters each. Time of flight (TOF), pulse height, and wire-chamber-position information were recorded for each particle detected in the recoil array. These data, together with the momentum and scattering angle of the particle detected in the LAS, provided an overconstrained signal for coincidence events. As a result, the background-to-signal ratio is very small despite the low ratio (0.07) of free to bound protons in the target material.

The field of the polarized-target magnet caused considerable curvature of the trajectories of the incident and final-state charged particles, leading to offsets in the measured scattering angles and interaction vertex. Further, this effect reduced the acceptance of LAS. A steering magnet was placed at the entrance of the spectrometer to increase the acceptance; this increase was particularly important for low-momentum scattered pions. Because reversal of the polarization was accomplished by a small, appropriate change in the microwave frequency, no change in the magnitude or sense of the magnetic field was required, ensuring that "spin-up" and "spin-down" data were taken under identical kinematical conditions.

The background was mainly produced by quasielastic scattering from carbon nuclei contained in the propanediol, ^{3}He and ^{4}He coolant, and the walls of the target cell and the cryostat. The background was measured in separate runs with the propanediol replaced by carbon beads with approximately the same number of carbon nuclei as contained in the propanediol target. The background-to-signal ratio for coincidence measurements was typically 10%, while the measurement in which only pion was detected had a one-to-one background-to-signal ratio.

For each accepted event we recorded the pulse height in all struck scintillators, the TOF through LAS, the recoil TOF, and the position data from all wire chambers. In the off-line analysis, the LAS wire-chamber data were used to calculate (i) the particle momentum, (ii) the apparent interaction point in the target, and (iii) the angle between the trajectory of the particle in LAS following the bend and the central ray in both horizontal and vertical planes. Parameter (ii) was used to reject events not originating in the target cell volume and parameter (iii) was used to reject events in which the scattered pion decayed to a muon and a neutrino. Each data run was replayed in several passes in which cuts were applied to an increasing number of parameters in the following order: LAS TOF, LAS scintillator pulse height, recoil TOF and scintillator pulse height, target projection, and muon rejections and the recoil wire-chamber data. In the single-arm measurement (i.e., when just the pion was detected) only the LAS-TOF, pulse-height, target-projection, and muon-rejection cuts were used. At each scattering angle, identical cuts were used for runs with target polarization up and down, and for background runs. Following each pass the analyzing power was calculated from

$$A_N = \frac{1}{p_T} \frac{\uparrow - \downarrow}{\uparrow + \downarrow - 2B} , \tag{1}$$

where p_T is the target polarization, $\uparrow$ = number of spin-up events, $\downarrow$ = number of spin-down events, and B = number of background events normalized to the pion-decay telescope monitors. The value obtained for A_N in each pass was compared with its value from the previous pass for consistency.

The momentum spectrum of the scattered pions of all events that have passed all our cuts contain a prominent peak on top of a small, nearly flat background spectrum. When the normalized spin-up yield, $\uparrow$, is subtracted from the $\downarrow$ yield the remaining events outside the peak region are consistent with zero. This demonstrates that the normalization of the data runs was done properly. Taking the combination $\uparrow + \downarrow - 2B$, again only events in the peak region remain, showing that the background normalization is correct. The results of these tests are also consistent with the background being independent of target polarization.

Our results for the analyzing power are presented in Figs. 1(a)–1(d). Also shown are the predictions of the partial-wave analyses by the KH (Ref. 3), CMU-LBL (Ref. 4), and VPI (Ref. 6) groups; none of these analyses include the present data. Only statistical errors are shown. The systematic error is ±3% due to the uncertainty in the absolute calibration of the target polarization.

The present data are compared with the predictions of the three recent phase-shift analyses in Figs. 1(a)–1(d). The PWA results approach −1.0 at forward angles, but our data have somewhat smaller magnitudes. The agreement with our data at 471 MeV/c is good beyond 60°, with the exception of the most backward angle point, where the disagreement is 5 standard deviations (SD). At 547 MeV/c the agreement is good at large angles but differences of as much as 6 SD are seen at *forward angles.* At 625 MeV/c the disagreement at large angles is of the order of 5 SD and at forward angles up to 9 SD. Finally, at 687 MeV/c the agreement is good at forward angles, with differences of 4 SD at backward angles. The large positive peak seen at backward angles shifts forward and is compressed in width as the incident momentum increases. The most dramatic change occurs between 625 and 687 MeV/c, leading to a second minimum at backward angles at 687 MeV/c.

Comparison of our data at 687 MeV/c with the data of Bekrenev *et al.*[21] at 685.5 MeV/c shows good agreement at forward angles, but their results are slightly lower than our measurements at backward angles [see Fig. 1(e)]. Given the trend of the angular distributions with momentum, the differences could be accounted for by slightly shifting upward the central momentum of the measurement of Bekrenev *et al.* by a few MeV/c. Our 625-MeV/c data are compared with the work of Bareyre *et al.*[22] at 616 MeV/c in Fig. 1(f). They have measured the recoil-proton polarization (P), which is equivalent to our asymmetry data by the $P=A$ theorem. The agreement is reasonable, keeping in mind the great momentum dependence of A_N and the uncertainties in Bareyre's results associated with the use of limited analyzing power data for carbon used in that experiment.

Other measurements of A_N at energies in the region of our data have been reported in the literature by Cox *et al.*,[23] Bizard *et al.*,[24] Chamberlain *et al.*,[25] and Arens *et al.*;[26] a measurement of the polarization parameter in this region has been made by Eandi *et al.*[27] The results of these experiments contain systematic errors of ±10% and therefore have minimal influence on the PWA's compared to this experiment. These data agree in shape with our data.

Whereas in $\pi^+p \rightarrow \pi^+p$ only $I=\frac{3}{2}$ amplitudes are involved, in $\pi^-p \rightarrow \pi^-p$ both $I=\frac{1}{2}$ and $I=\frac{3}{2}$ amplitudes contribute. In our earlier work[18] on $A_N(\pi^+p \rightarrow \pi^+p)$ we investigated the $I=\frac{3}{2}$ amplitudes. Using the VPI scattering analysis interactive dial-in (SAID) program we added our $A_N(\pi^+p \rightarrow \pi^+p)$ data to the VPI data base to obtain a new, single-energy PWA. Our data did not change any phase significantly. Though the scope of such a single-energy analysis is clearly limited, the results indicate that the $I=\frac{3}{2}$ amplitudes are well determined. Thus, the addition of our $A_N(\pi^-p \rightarrow \pi^-p)$ data to the VPI data base for single-energy solutions could be expected to affect only the $I=\frac{1}{2}$ partial waves; this is, indeed, observed. At 471 and 547 MeV/c the changes are insignificant. At 625 MeV/c the P_{11} phase decreases from 56° to 54° and D_{13} decreases from 36° to 32°. The effects are even larger at 687 MeV/c, where P_{11} increases from 86° to 98° (a change of 12°), and at the same time S_{11} decreases from 26° to 23°, D_{13} from 58° to 55°, and D_{15} from 13° to 9°. Thus we conclude that the current PWA's do not describe correctly the Roper resonance. A new, full analysis requires data on π^-p elastic and charge-exchange scattering.

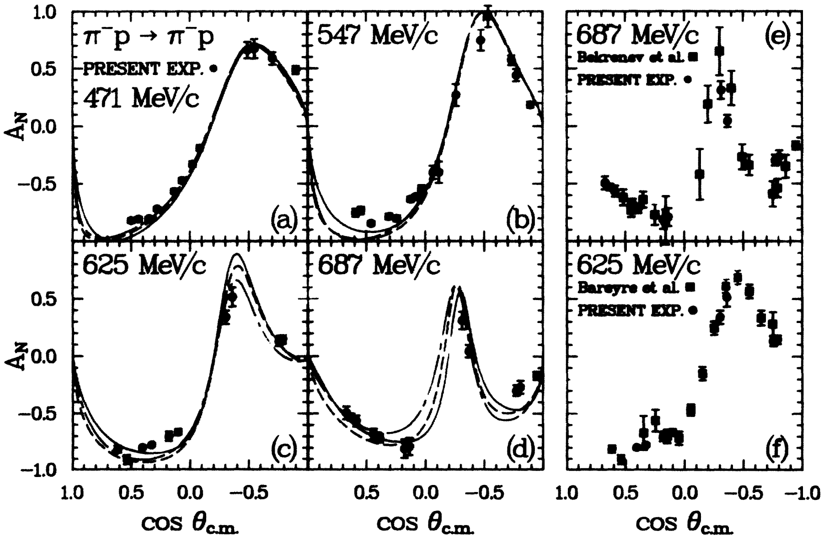

FIG. 1. (a)–(d) Analyzing power A_N measured in π^-p elastic scattering using a transversely polarized target at incident pion momenta of 471, 547, 625, and 687 MeV/c. The curves are the predictions of three partial-wave analyses by KH (Ref. 3) (solid curves), CMU-LBL (Ref. 4) (short-dash–long-dash curves), and VPI (Ref. 6) (dashed curves). (e) Comparison of present data at 687 MeV/c with those of Bekrenev *et al.* (Ref. 21) at 685.5 MeV/c (560 MeV). (f) Comparison of present data at 625 MeV/c with those of Bareyre *et al.* (Ref. 22) at 616 MeV/c (492 MeV).

We gratefully acknowledge the loan of the polarized target by J. E. Simmons and LANL P division and the extensive help of J. G. J. Boissevain in the initial setup of the target. We thank R. A. Arndt and L. D. Roper for making available the interactive phase-shift program SAID. This work was supported in part by the U.S. Department of Energy.

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