PHYSICAL REVIEW C VOLUME 42, NUMBER 5 NOVEMBER 1990

Comparison of the vector analyzing power iT_{11} for $\pi^{\pm}d$ scattering at 180 MeV

R. Tacik,* E. T. Boschitz, W. Gyles, and M. Wessler
Kernforschungszentrum Karlsruhe, Institut für Kernphysik and Institut für Experimentelle Kernphysik der Universität Karlsruhe, 7500 Karlsruhe, Federal Republic of Germany

S. Mango, B. van den Brandt, and J. A. Konter
Paul Scherrer Institut, 5232 Villigen PSI, Switzerland

D. R. Gill and P. Weber
TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia, Canada

(Received 27 December 1989)

The vector analyzing power iT_{11} has been measured for the first time for π^+d and π^-d elastic scattering at $T_\pi = 180$ MeV in the angular range between 50° and 110°, using a polarized deuteron target and a magnetic spectrometer. The data are compared with theoretical calculations involving different Coulomb prescriptions.

I. INTRODUCTION

The πNN system is of considerable interest because it is the simplest three-body system, and can, in principle, be calculated exactly from the elementary pion-nucleon and nucleon-nucleon interactions. There has been considerable progress in both experimental and theoretical investigations over the last ten years. Experimentally, advances in polarized target techniques have enabled the measurement of all three tensor spin observables in the $\pi^+d \rightarrow \pi^+d$ reaction.[1,2] Simultaneously, precise data have been obtained for the vector analyzing power iT_{11}. Theoretically, three-body calculations have achieved a high degree of sophistication.[3] There remain persistent discrepancies, however, between all theoretical predictions and the measured differential cross sections at backward angles, and the vector analyzing power at forward angles, above $T_\pi = 180$ MeV. It has been suggested recently that these discrepancies can be overcome by introducing an explicit short-ranged $N\Delta$ interaction,[4] which is not contained in the standard theories. In particular, analysis of the new precise iT_{11} data provided evidence for strong repulsion in the ${}^3S_1N\Delta$ channel,[5] which is consistent with the interpretation of other experimental results[6,7] and quark model predictions.[8] It is important to note, however, that all three-body theories exclude consideration of Coulomb effects. As we approach the stage where comparison between theory and experiment takes place on a quantitative rather than qualitative level, this appears to be a serious omission.

Another topic of recent interest involving the πd system has been the study of charge symmetry breaking. After removal of electromagnetic effects, which are not charge symmetric, observables measured for π^+d should be the same as those for π^-d, provided hadronic charge symmetry is not broken. The first relevant experiment was that of Pedroni *et al.*,[9] who measured $\pi^{\pm}d$ total cross sections between 70 and 370 MeV. After applying Coulomb corrections, energy-dependent differences were found, varying from -8% at $T_\pi = 143$ MeV to $+3\%$ at $T_\pi = 256$ MeV. These effects were parametrized in terms of mass and width differences between the Δ isobars and compared to quark model predictions. This work was followed up by a series of measurements of $\pi^{\pm}d$ elastic differential cross sections: Balestri *et al.*[10] performed measurements at 65 MeV, but could not draw any conclusions. Masterson *et al.*[11] performed measurements at 143 MeV and concluded in a first publication that charge symmetry is valid; but in two subsequent papers,[12,13] where data taken at 256 MeV were also presented and the calculation of the Coulomb corrections was improved, charge-symmetry-breaking effects were reported. The most recent measurement by Smith *et al.*[14] at $T_\pi = 143$, 180, 220, and 256 MeV was in agreement with that of Masterson *et al.* provided the earlier data were renormalized to new, more precise $\pi^{\pm}p$ data. The results of Smith *et al.* were also used to extract Δ-isobar mass and width parameters.

The determination of charge symmetry breaking effects from $\pi^{\pm}d$ experiments is clearly a challenging task. Experimentally, the measurement of absolute cross sections on the level of 1% is very difficult. Theoretically, there is the question of how to treat the external Coulomb corrections (pure Coulomb, Coulomb-nuclear interference, and finite deuteron size effects), and internal Coulomb perturbations (mass differences between the neutron and the proton, mass and width differences among the intermediate Δ isobars, and the Δ's self-energy). These topics have been discussed in detail by Rinat and Alexander,[15] and more recently by Fröhlic *et al.*,[16] in addition to the discussions in the previously mentioned experimental papers. Fröhlic *et al.* concluded that the reliability of the different Coulomb treatments must be carefully investigated before one may extract information on charge symmetry breaking; and demonstrated that the vector analyzing power iT_{11} is more sensitive to different Coulomb prescriptions than either $d\sigma/d\Omega$ or the tensor polarization t_{20}.

The purpose of the present experiment was to provide the first measurement of iT_{11} in $\pi^- d$ scattering, and to compare it to the $\pi^+ d$ result. The total cross-section asymmetry measured by Pedroni *et al.*[9] passed through zero at 180 MeV; and only minimal charge symmetry breaking effects are predicted[17,14] for the differential cross-section asymmetry at this energy. Thus, an incident pion energy near $T_\pi = 180$ MeV was chosen in order to concentrate on external Coulomb effects.

II. EXPERIMENT

The experiment was performed with the πM1 beam at the Paul Scherrer Institute (PSI, formerly SIN) in Switzerland. Many experimental details, especially on the polarized target setup, can be found in Ref. 1. Note however, that in the present experiment the SUSI magnetic spectrometer was used rather than the time-of-flight scintillation counter telescopes described in Ref. 1. The π^- data were taken at $T_\pi = 175.2$ MeV in a relatively short time, during a long beam period devoted to measuring iT_{11} and τ_{22} at forward angles, at several energies, with π^+.[18] The configuration was changed from π^+ to π^- by reversing the polarities of all the magnetic elements in the channel, of the superconducting Helmholtz coil of the polarized target, and of the spectrometer. In this way the entire setup was kept charge symmetric, which is a definite advantage over the πd coincidence technique, where the trajectories of the recoil deuterons are different for the two polarities of the target field. Of course the larger solid angle of a multicounter setup can substantially reduce data taking time.

In order to achieve sufficient energy resolution in the πd spectra, a 64-element hodoscope was used at the intermediate dispersed focus of the πM1 beam line. Only single hits were counted. In addition, a five-element hodoscope (S1) positioned 1 m upstream of the target was used to provide a better measure of the incident beam angle. Finally, a small beam-defining counter (S2) was positioned 16 cm upstream of the target. The incident pion flux was measured directly by scaling the coincidence (HODO)$\cdot$S1$\cdot$S2$\cdot\overline{\text{S2}}\cdot$rf. Here, $\overline{\text{S2}}$ represents the S2 counter signal triggered at a high level, and is used to reject those protons not already removed from the beam by the πM1 electrostatic separator. The coincidence requirement with the rf (pickup of the PSI cyclotron frequency) is used to reject muon and electron beam contamination. Typical incident beam fluxes were 3.6×10^6 π^+/sec and 1.1×10^6 π^-/sec.

It was found that due to mechanical stresses, the center of rotation of the spectrometer did not correspond to the center of its pivot support. The polarized target was thus mounted on a platform independent of the spectrometer.

Data were taken in several cycles of alternating positive, zero, and negative target polarizations. Due to the relatively long polarizing times, however, it was impractical to cycle the polarization at each spectrometer angle. Thus, an entire angular distribution was measured before the target polarization was changed. This procedure should not introduce large systematic uncertainties, however, since it was verified that the spectrometer angle setting could be reproduced to about 0.01°.

The values for iT_{11} for each pion polarity at each spectrometer angle were determined in a number of ways, as described in Refs. 1 and 2, to ensure that there were no systematic effects. The general expression for iT_{11} is

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

which reduces to

$$iT_{11} = \frac{1}{2\sqrt{3}p_z} \frac{\sigma^+ - \sigma^-}{\sigma^0}$$

if the target positive and negative vector polarizations are equal ($p_z^+ = p_z^-$). The target tensor polarization p_{zz} is related to the vector polarization by $p_{zz} = 2 - (4 - 3p_z^2)^{1/2}$. The quantities σ^+, σ^-, and σ^0 are the relative elastic-scattering cross sections for positive, negative, and zero target polarizations, given by $\sigma = \text{yield}/(N_\pi \epsilon)$, where N_π is the number of incident pions, and ϵ is the combined spectrometer wire chamber and computer efficiency. Note that knowledge of such factors as the spectrometer solid angle and the absolute number of target nuclei is not required because iT_{11} is determined as a ratio of cross sections. In particular, iT_{11} is not sensitive to the absolute pion fraction in the beam, as long as it remains constant; nor is it sensitive to radiative corrections, which are different for π^+ and π^-. For consistency, estimates were made for all of these quantities and absolute differential cross sections determined. These were in good agreement with published values. Also, the asymmetry

$$A_\pi = \frac{d\sigma/d\Omega(\pi^-) - d\sigma/d\Omega(\pi^+)}{d\sigma/d\Omega(\pi^-) + d\sigma/d\Omega(\pi^+)} \qquad (1)$$

was calculated and compared with the data of Smith *et al.*[14] Consistency was found. A detailed comparison of iT_{11} measured with π^+ in the present experiment with earlier results[19,2] will be presented elsewhere.[18]

The target was polarized by microwave irradiation in a magnetic field of 2.5 T. Positive and negative polarizations were obtained with slightly different microwave frequencies, and did not involve reversing the polarity of the target magnetic field. The target polarization was determined by comparing the areas of the dynamically enhanced and thermal equilibrium NMR signals. Typical polarizations were ± 0.35. Further details can be found in Ref. 1. One difference in the present experiment was the fact that the target material was in the form of a solid block ($5\times18\times18$ mm^3) rather than small beads. This made background subtraction easier, which was accomplished by replacing the deuterated propandiol in the foreground target with ordinary propandiol of the same areal density.

The overall energy resolution was ~ 2.4 MeV, which did not enable a clean separation of pions from the $\pi^\pm d \to \pi^\pm d$ elastic and $\pi^\pm d \to \pi^\pm pn$ breakup reactions. The yield of $\pi^\pm d \to \pi^\pm d$ pions could be reliably determined, however, by fitting the tail of the breakup distribution and subtracting it from the elastically scattered pion peak. It should be noted that the situation is further complicated by the fact that there are polarization effects for the breakup reaction. This did not present a serious problem, however, because it was found that these affected only the magnitude, and not the shape of the tail of the breakup distributions.

III. RESULTS AND DISCUSSION

In their study of the effects of a refined Coulomb treatment on $\pi^{\pm}d$ elastic-scattering observables, Frölich *et al.*[16] presented their results in terms of an asymmetry parameter $A_{iT_{11}}$ defined, in analogy to the parameter A_{π} defined in Eq. (1), as

$$A_{iT_{11}}=\frac{(iT_{11})_{\pi^-}-(iT_{11})_{\pi^+}}{(iT_{11})_{\pi^-}+(iT_{11})^{\pi^+}} .$$

An alternate method of presentation is simply the difference of $\pi^{\pm}$ measurements:

$$\Delta_{iT_{11}}=(iT_{11})_{\pi^-}-(iT_{11})_{\pi^+} .$$

The need for an alternate presentation stems from the fact that, unlike $d\sigma/d\Omega$, iT_{11} can be equal to zero, in which case $A_{iT_{11}}$ becomes insensitive to $\pi^{\pm}$ differences. That is, as $iT_{11}\rightarrow 0$, the uncertainly $\Delta(A_{iT_{11}})\rightarrow\infty$, even though the uncertainties in the measured values of iT_{11} can be quite small. As iT_{11} is already a ratio of cross-section measurements, neither $A_{iT_{11}}$ nor $\Delta_{iT_{11}}$ is sensitive to such factors as absolute target thickness or counter solid angle. However, there is an overall 10% systematic uncertainty in the individual values of iT_{11} due to the uncertainty in the absolute value of the target polarization. This uncertainty is present in $\Delta_{iT_{11}}$, but not in $A_{iT_{11}}$. Thus, we have chosen to present our data in the form of both $A_{iT_{11}}$ and $\Delta_{iT_{11}}$ in Fig. 1, where we compare our results with predictions from Fröhlic *et al.* The labeling (a)–(e) of the various curves is the same as that used in Ref. 16, and represents an increasing sophistication of the treatment of Coulomb effects. In a simplified notation, the total amplitude can be expressed as

$$f_{\text{tot}}=f_{\text{Coul}}+f_{\text{sc}} ,$$

where f_{Coul} is the pure Coulomb amplitude, and the partial-wave decomposed Coulomb-modified hadronic amplitude can be written

$$f_{\text{sc},ll'}=e^{i(\delta l+\delta l')}T_{\text{sc},ll'}$$

where δl are Coulomb phases, and $T_{\text{sc},ll'}$ are the matrix elements of the Coulomb-corrected strong amplitudes. There are thus three places where Coulomb effects enter into the calculation of f_{tot}, and an increase in sophistication involves moving from a point-charge approximation to inclusion of the charge extent of both the pion and the

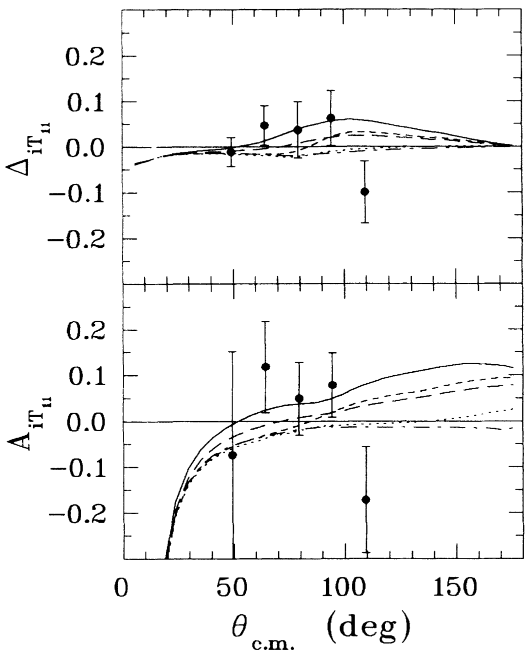

FIG. 1. Present results for $A_{iT_{11}}$ and $\Delta_{iT_{11}}$ compared with theoretical predictions of Fröhlic *et al.*[16] In the notation of Ref. 16, the dot-dashed curve corresponds to calculation (a), the dotted curve to (b), the short-dashed curve to (c), the long-dashed curve to (d), and the solid curve to (e).

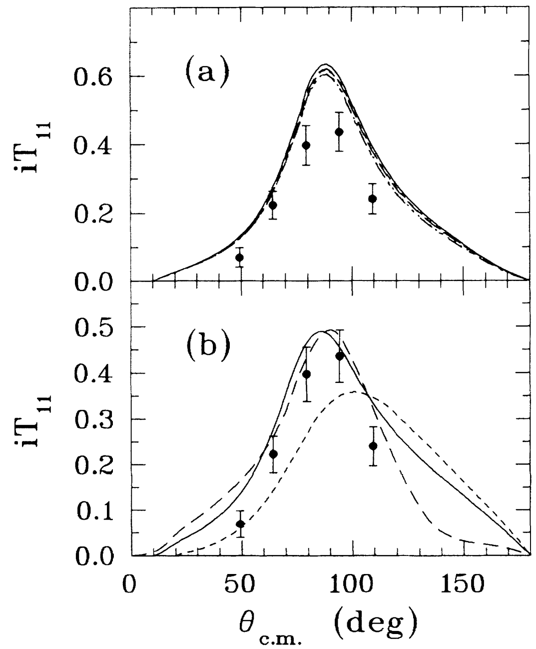

FIG. 2. Present results for iT_{11} for $\pi^- d$ elastic scattering compared with various theoretical predictions. In (a), all curves correspond to calculations of Ref. 16, and are labeled as in Fig. 1. In (b), the solid, long-dashed, and short-dashed curves were calculated using the hadronic amplitudes of Refs. 21, 20, and 22, respectively.

deuteron, and an addition of relativistic corrections.

Unfortunately, no clear conclusion can be drawn from the comparison in Fig. 1 because of the large size of the experimental error bars, which are primarily a reflection of the short time taken in accumulating the π^- data.

It should be pointed out that the individual $\pi^{\pm}d$ iT_{11} values are not very well reproduced by the calculations of Ref. 16. A comparison with the π^- data is shown in Fig. 2(a). This raises the question of how sensitive predictions of Coulomb effects are to the hadronic amplitudes used in the calculations. To investigate this, we have performed calculations using three different hadronic amplitudes: those of Thomas and Rinat,[21] those of Blankleider and Afnan,[20] and those taken from a phase-shift analysis to available data by Stevenson and Shin;[22] and incorporated the Coulomb treatment of Rinat and Alexander,[15] which unfortunately does not correspond exactly to any of the five approximations used by Fröhlic *et al.* The results for $\pi^- d$ iT_{11} are shown in Fig. 2(b). The results for $A_{iT_{11}}$ and $\Delta_{iT_{11}}$ are compared to the present measurements in Fig. 3. It is evident that while the three calculations for iT_{11} vary greatly, the calculations of the asymmetry parameters, especially $\Delta_{iT_{11}}$, do not differ very much. It would thus appear that the asymmetry data are more sensitive to various Coulomb prescriptions, than to various hadronic amplitudes.

In summary, in an exploratory experiment, we have measured iT_{11} for the $\pi^- d \rightarrow \pi^- d$ reaction, for the first time. Combined with π^+ measurements, these data were presented in the form of asymmetry parameters $A_{iT_{11}}$ and $\Delta_{iT_{11}}$. A comparison was made with calculations using different Coulomb prescriptions, but no definite conclusions could be drawn. A comparison with calculations using the same Coulomb prescription, but different hadronic amplitudes, showed little sensitivity, at least at this energy. It would be of interest to extend the present investigation to both lower and higher incident pion energies, where Coulomb effects are predicted to be larger. In fact, such a program has been proposed at TRIUMF.[23]

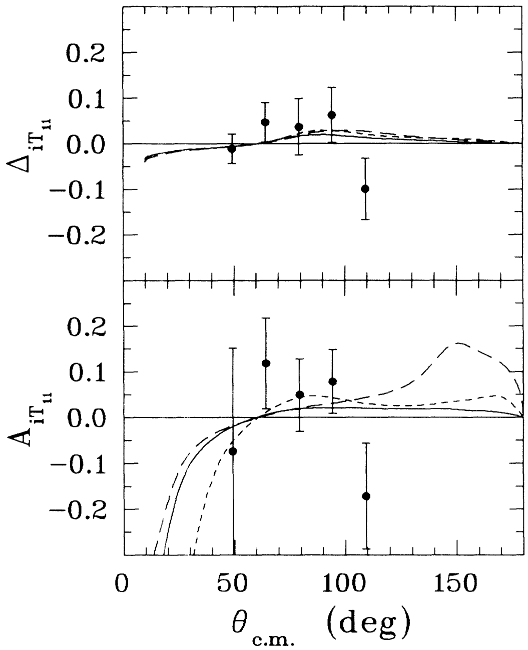

FIG. 3. Present results for $A_{iT_{11}}$ and $\Delta_{iT_{11}}$ compared with theoretical predictions of Ref. 21 (solid curve), Ref. 20 (long-dashed curve), and Ref. 22 (short-dashed curve).

The polarized target material was kindly provided by Dr. T. O. Niinikoski, CERN. We thank Dr. B. Saghai for sending us the unpublished theoretical predictions for the different Coulomb treatments for several energies. This work would have been impossible without the generous help and considerable skills of the staff of PSI. It was supported by the Bundesministerium für Forschung und Technologie of the Federal Republic of Germany.

---

*Present address: Department of Physics, University of Regina, Regina, Saskatchewan, Canada S4S 0A2.

[1] C. R. Ottermann, E. T. Boschitz, W. Gyles, W. List, R. Tacik, M. Wessler, S. Mango, B. van den Brandt, J. A. Konter, D. R. Gill, and G. R. Smith, Phys. Rev. C **38**, 2296 (1988).

[2] C. R. Ottermann, E. T. Boschitz, H. Garcilazo, W. Gyles, W. List, R. Tacik, M. Wessler, S. Mango, B. van den Brandt, J. A. Konter, and E. L. Mathie, Phys. Rev. C **38**, 2310 (1988).

[3] H. Garcilazo and T. Mizutani, Few-Body Syst. **5**, 127 (1988).

[4] E. Ferreira, S. C. B. de Andrade, and H. G. Dosch, Phys. Rev. C **36**, 1916 (1987).

[5] E. Ferreira and H. G. Dosch, Phys. Rev. C **40**, 1750 (1989).

[6] T. Takaki, Ann. Phys. **166**, 1 (1986).

[7] R. Nagaoka and K. Ohta, Ann. Phys. **184**, 148 (1988).

[8] M. Oka and K. Yazaki, in *International Review of Nuclear Physics*, edited by W. Weise (World Scientific, Singapore, 1984), Vol. 1, p. 490.

[9] E. Pedroni, K. Gabathuler, J. J. Domingo, W. Hirt, P. Schwaller, J. Arvieux, C. H. Q. Ingram, P. Gretillat, J. Piffaretti, N. W. Tanner, and C. Wilkin, Nucl. Phys. **A300**, 321 (1978).

[10] B. Balestri, G. Fournier, A. Gerard, J. Miller, J. Morgenstern, J. Picard, B. Saghai, P. Vernin, P. Y. Bertin, B. Coupat, E. W. A. Lingeman, and K. K. Seth, Nucl. Phys. **A392**, 217 (1983).

[11] T. G. Masterson, E. F. Gibson, J. J. Kraushaar, R. J. Peterson, R. S. Raymond, R. A. Ristinen, and R. L. Boudrie, Phys. Rev. Lett. **47**, 220 (1981).

[12] T. G. Masterson, J. J. Kraushaar, R. J. Peterson, R. S. Raymond, R. A. Ristinen, R. L. Boudrie, E. F. Gibson, and A. W. Thomas, Phys. Rev. C **26**, 2091 (1982).

[13] T. G. Masterson, J. J. Kraushaar, R. J. Peterson, R. S. Raymond, R. A. Ristinen, J. L. Ullmann, R. L. Boudrie, D. R. Gill, E. F. Gibson, and A. W. Thomas, Phys. Rev. C **30**, 2010 (1984).

[14] G. R. Smith, D. R. Gill, D. Ottewell, G. D. Wait, P. Walden, R. R. Johnson, R. Olszewski, R. Rui, M. E. Sevior, R. P. Trelle, J. Brack, J. J. Kraushaar, R. A. Ristinen, H. Chase, E.

L. Mathie, V. Pafilis, R. B. Schubank, N. R. Stevenson, A. Rinat, and Y. Alexander, Phys. Rev. C **38**, 240 (1988).

[15] A. S. Rinat and Y. Alexander, Nucl. Phys. **A404**, 476 (1983).

[16] J. Fröhlic, B. Saghai, C. Fayard, and G. H. Lamot, Nucl. Phys. **A435**, 738 (1985).

[17] T. G. Masterson, Phys. Rev. C **31**, 1957 (1985).

[18] M. Wessler *et al.* (to be submitted to Phys. Rev. C).

[19] G. R. Smith, E. L. Mathie, E. T. Boschitz, C. R. Ottermann, S. Mango, J. A. Konter, M. Daum, M. Meyer, R. Olszewski, and F. Vogler, Phys. Rev. C **29**, 2206 (1984).

[20] B. Blankleider and I. Afnan, Phys. Rev. C **24**, 1572 (1981).

[21] A. W. Thomas and A. S. Rinat, Phys. Rev. C **20**, 216 (1979).

[22] N. R. Stevenson and Y. M. Shin, Phys. Rev. C **36**, 1221 (1987).

[23] TRIUMF experimental proposal 559, D. R. Gill spokesman (unpublished).