$\pi^{\pm}p$ differential cross sections at low energies

H. Denz [a,*], P. Amaudruz [b], J.T. Brack [c], J. Breitschopf [a], P. Camerini [d,e], J.L. Clark [f], H. Clement [a],
L. Felawka [b], E. Fragiacomo [e], E.F. Gibson [g], N. Grion [e], G.J. Hofman [b,h], B. Jamieson [b],
E.L. Mathie [h], R. Meier [a], G. Moloney [f], D. Ottewell [b], O. Patarakin [i], J.D. Patterson [c], M.M. Pavan [b],
S. Piano [d,e], K. Raywood [b], R.A. Ristinen [c], R. Rui [d,e], M.E. Sevior [f], G.R. Smith [b,j], J. Stahov [k],
R. Tacik [h], G.J. Wagner [a], F. von Wrochem [a], D.M. Yeomans [h]

[a] *Physikalisches Institut, Universität Tübingen, D-72076 Tübingen, Germany*
[b] *TRIUMF, Vancouver, British Columbia, Canada V6T 2A3*
[c] *University of Colorado, Boulder, CO 80309-0446, USA*
[d] *Dipartimento di Fisica dell'Università di Trieste, I-34127 Trieste, Italy*
[e] *Istituto Nazionale di Fisica Nucleare, I-34127 Trieste, Italy*
[f] *School of Physics, University of Melbourne, Parkville, Victoria 3052, Australia*
[g] *California State University, Sacramento, CA 95819, USA*
[h] *University of Regina, Regina, Saskatchewan, Canada S4S 0A2*
[i] *Kurchatov Institute, Moscow, Russia*
[j] *Jefferson Lab, Newport News, VA 23006, USA*
[k] *University Tuzla, Faculty of Science, 35000 Tuzla, Bosnia and Herzegovina*

Abstract

Differential cross sections for π^-p and π^+p elastic scattering were measured at five energies between 19.9 and 43.3 MeV. The use of the CHAOS magnetic spectrometer at TRIUMF, supplemented by a range telescope for muon background suppression, provided simultaneous coverage of a large part of the full angular range, thus allowing very precise relative cross section measurements. The absolute normalisation was determined with a typical accuracy of 5%. This was verified in a simultaneous measurement of muon proton elastic scattering. The measured cross sections show some deviations from phase shift analysis predictions, in particular at large angles and low energies. From the new data we determine the real part of the isospin forward scattering amplitude.
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Pion–nucleon scattering at low energies allows the study of non-perturbative aspects of QCD on one of the simplest hadronic systems. The prime example is the determination of the πN-sigma term which is a measure of the explicit breaking of chiral symmetry through non-vanishing quark masses [1]. However, the reported values range from the canonical 64 MeV [2] to about 80 MeV [3] and there is a longstanding dispute

whether this scatter is due to the method of extraction or due to the data base used (or both). A solution of the puzzle is highly desirable, all the more since, with the conventional understanding [1], values around 80 MeV would imply a strange sea quark content of the nucleon which is at variance with our current understanding of its structure.

Independent of theoretical considerations the data base at pion kinetic energies below 50 MeV is scarce and, where existing, sometimes contradictory. Low energy data are of considerable importance since the determination of the sigma term

* Corresponding author.
E-mail address: denz@pit.physik.uni-tuebingen.de (H. Denz).

requires an extrapolation of the scattering amplitudes to the unphysical Cheng–Dashen point [4] below the πN threshold. While observables at the threshold (i.e., scattering lengths) are being determined by precision measurements of pionic hydrogen [5], the energy dependence of the phase shifts, which is required for the extrapolation, remains largely uncertain. This is due to the experimental difficulties inherent in πp scattering experiments at low energies, where the pion decay lengths are small and the resulting muon background presents a severe problem.

The present experiment exploits the properties of the CHAOS spectrometer [6] at the M13 low-energy pion channel of TRIUMF. The spectrometer is well suited for low energy pion scattering measurements since it has a compact design and allows a simultaneous measurement of almost the full angular distribution. Briefly, CHAOS (see Fig. 1) is a magnetic spectrometer with a 2π acceptance in the reaction plane and a $\pm 7°$ acceptance out-of-plane. It consists of an axially symmetric dipole magnet with a pole diameter of 96 cm. The target in its center is surrounded by four concentric rings of wire chambers. This tracking region is surrounded by fast trigger counters consisting of plastic scintillation counters and lead glass Cerenkov blocks. For this experiment (see Fig. 1) blocks at forward scattering angles were removed and replaced by a range telescope [7]. Information from this telescope was interpreted using a software neural network to discriminate scattered pions from the huge background of decay muons.

The target consisted of 80 cm^3 of liquid hydrogen contained in a cell with flat rectangular Mylar windows 125 μm thick and 1.25 cm apart. It was surrounded by an outer cell filled by hydrogen gas of the same pressure to ensure flat target windows. Data were taken with and without liquid hydrogen for background subtraction.

The experiment used positively and negatively charged pions with energies of 19.9 ± 0.3, 25.8 ± 0.3, 32.0 ± 0.3, 37.1 ± 0.4, and 43.3 ± 0.4 MeV from the M13 channel of TRIUMF. The uncertainties follow from a time of flight calibration of the pion channel using the method described in [8]. Muons and electrons from the production target were discriminated from pions by their time of flight as taken from the cyclotron RF pulse and a time signal derived from a thin "finger" scintillation counter (see Fig. 1) at the entrance of CHAOS.

The data were taken with a two-stage trigger system. The first level trigger required a hit in the finger counter with the correct time of flight for pions or muons through the channel, no veto in any of the veto counters, and at least one hit in first layer of the range telescope or the CFT blocks. The second level trigger rejected events with hit patterns typical for unscattered beam particles using information from the inner two wire chambers.

Incoming and outgoing particles were detected in the wire chambers. Momenta, vertices and scattering angles were reconstructed from the hits in the wire chambers. It is noteworthy that the out-of-plane-component of the scattering angle was also determined using cathode strips and resistive wires. Only events fulfilling the kinematics of elastic pion–proton scattering were accepted. Furthermore, valid vertices were required to
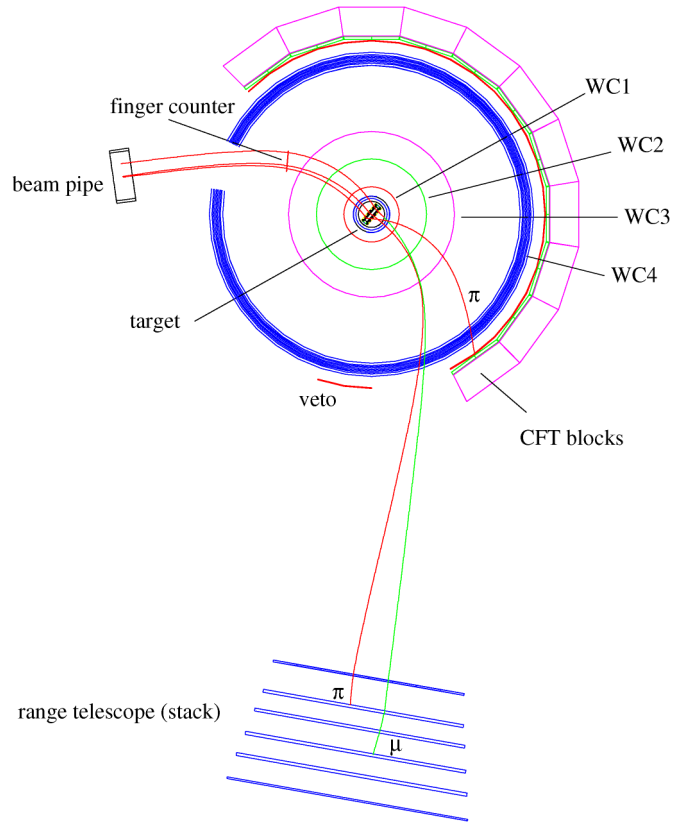

Fig. 1. Experimental setup: The magnetic field of CHAOS is oriented perpendicular to the plane of the figure. The fourth wire chamber (WC4) is surrounded by plastic scintillator and lead glass Cerenkov counters (CFTs). The range telescope consists of 6 layers of plastic scintillators and covers the forward scattering angles. Three typical events are plotted, a scattered pion detected by a CFT block, a scattered pion detected by the range telescope and a pion decaying into a muon in the target region which is then detected by the range telescope.

lie in the liquid hydrogen region. A range telescope [7] was installed in order to mitigate the otherwise large forward-angle background of muons from pion decay in the target region. The range telescope consisted of 6 layers of plastic scintillator. The first layer was segmented into 8 paddles allowing angle-dependent prescaling of events at forward angles. The hit of the kinematically correct paddle was also checked to ensure the absence of pion decay. Depending on the beam energy, suitable aluminum absorbers were inserted for the most sensitive response. Neural network training runs were taken with pions and muons identified by time of flight in the channel and directed directly onto the individual paddles. After training, the neural network achieved a 98% efficiency in pion-muon discrimination using the ΔE, range and time of flight information of the telescope.

The (energy-dependent) acceptance of the set-up was determined by GEANT3 [9] Monte Carlo simulations. Special care was taken to ensure a correct detector and target model including all materials. This is especially important for the lowest energies where energy losses play a significant role. For the backward angles at the lowest energy (19.9 MeV) the high sensitivity to the choice of material and geometry prevented a

reliable determination of the acceptance. At all energies angular regions of rapidly changing acceptance near the support pillars and the border between CFT and range telescope were discarded. Regions where the decay muon background was more than two orders of magnitude larger than the pion rate had to be discarded. The usual corrections for deadtime of the data acquisition system, chamber efficiencies, pion decay and pion flux reduction due to hadronic events were also applied.

In order to check the acceptance and the absolute normalisation of cross sections by lepton scattering [10], incident muons were selected by their time of flight in the channel. Muon-proton differential cross sections were measured at forward angles (up to 25 degrees) where they are sufficiently large. They were compared to calculated electromagnetic cross sections taking into account the proton charge distributions [11]. We observed good agreement of the relative angular distributions. The average ratio of measured to calculated differential cross sections agreed with unity within an error of $\pm 5\%$ which we take as the normalisation error of the pion cross sections. Exceptions are the data at 43 MeV where the error is larger ($\pm 7\%$) for statistical reasons, and at 37 MeV where the measured muon cross sections are consistently low by 8% leading to an asymmetric estimated normalization error ($+5, -9\%$). Details of the experiment and the cross sections in numerical form may be found in Ref. [12].

The results of the present experiment are summarized in Figs. 2 and 3 for $\pi^- p$ and $\pi^+ p$ scattering, respectively. A complete PSA of the cross sections over the full energy range with amplitudes constrained by analyticity and dispersion relations is beyond the scope of this Letter. Instead single-energy (SE) fits to our data were made. At each energy the phase shifts for S- and P-waves were adjusted simultaneously for $\pi^- p$ and $\pi^+ p$ scattering and the phase shifts for D- and F-waves were taken from the KH84 [15] solution and kept fixed. For comparison, Figs. 2 and 3 show the predictions from the SAID FA02 [13], KH80 [14] phase shift analysis (PSA) together with the SE fits. At first glance the data show an impressive overall agreement with the predictions. A closer look, however, reveals a general trend of the PSA predictions to lie above the data at low energies and large angles. The SE fits on the other hand are able to reproduce the data.

At energies below 30 MeV SAID tends to overestimate the $\pi^- p$ cross sections at large scattering angles, where the KH80 solution and the SE fit give better descriptions. A comparison with previous data shows that near 43 MeV our data and also the SAID solution lie just in-between the angular distributions as measured by Brack et al. [16] and by Joram et al. [17], respectively. The suppression near 40 degrees observed in the latter work is not seen, whereas the 175 degree data point by Janousch et al. [18] is confirmed. Near 32 MeV our cross sections agree with the PSA predictions whereas the results of Joram et al. [17] fall somewhat low beyond 80 degrees.

The situation for $\pi^+ p$ scattering is much more difficult. Near 25 degrees at 43.3 MeV the CNI minimum is substantially filled in, which is not seen in the three PSA results. At 19.9 MeV the CNI depression of the data is stronger than predicted by KH80. The simultaneously taken $\mu^+ p$ cross sections
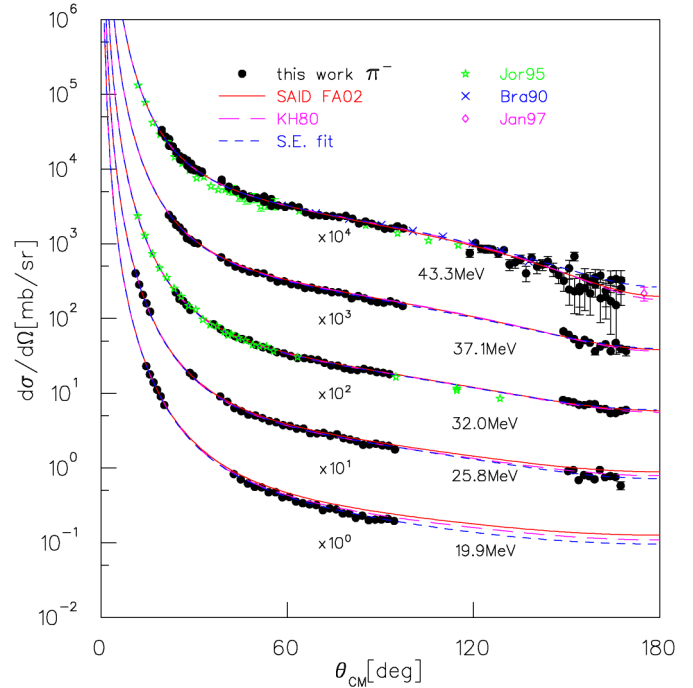

Fig. 2. Results of this experiment for $\pi^- p$ scattering together with phase shift solutions and results from other experiments at closeby energies. Bars denote statistical errors only. The absolute normalisation is uncertain by 5 to 9% (see text).
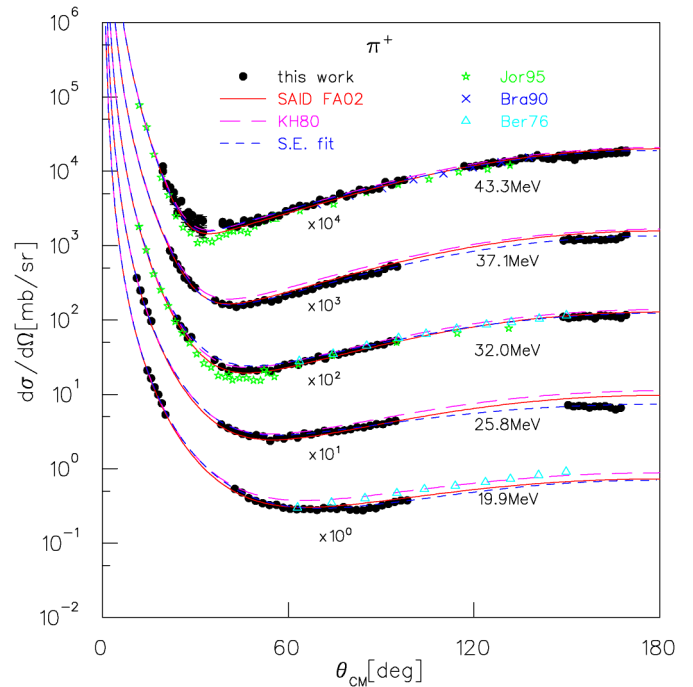

Fig. 3. As Fig. 2, but for $\pi^+ p$ scattering.

and also the $\pi^- p$ data do not show such an excess which suggests that it is not an artifact of the analysis. At larger angles the agreement with the 45.0 MeV data by Brack et al. [16] is satisfactory. The data of Joram et al. [17] near 45 MeV and 32 MeV exhibit an even deeper minimum than the SAID fit and fall substantially below our data at backward angles. A general
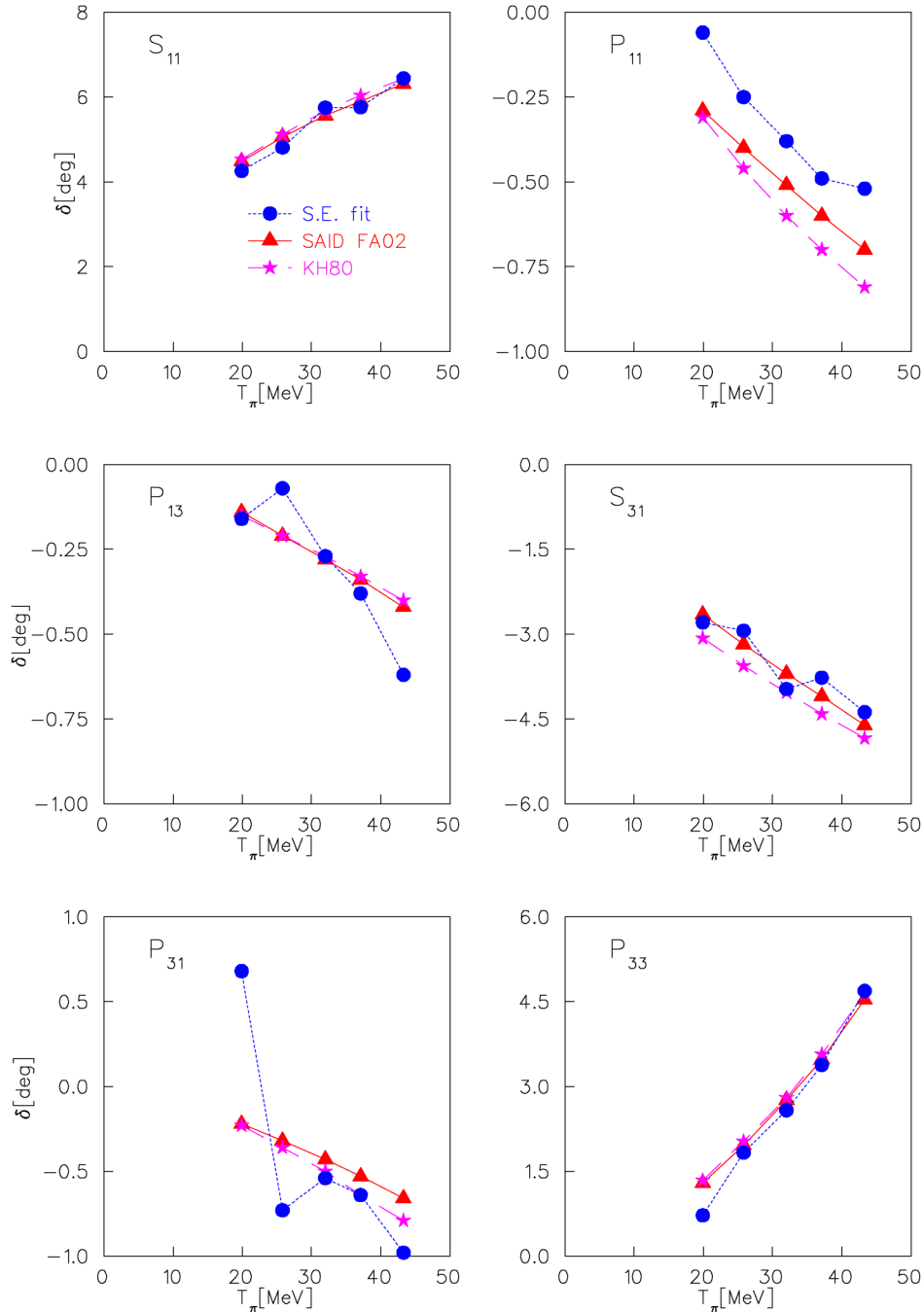
Fig. 4. Energy dependence of s- and p-wave phase shifts.

feature of our data is that the slope of the angular distributions (relative to the SAID fits) increases with decreasing energy. The discrepancy between our results and those of Bertin et al. [19] at 20.8 MeV is obvious. Clearly this data supports the previous criticism of the data sets [17] and [19] by Fettes and Matsinos [20].

As shown in Fig. 4, the S_{11}, S_{31} and P_{33} phase shifts determined in the SE fits are very close to the SAID FA02 and KH80 solutions, with the former being slightly favoured by the S_{31} phases. This agreement is somewhat in contrast to the findings of Joram et al. [17], where the S_{11} and S_{31} phases were found to be significantly smaller by about 1 degree, i.e. by 15–

30%. The main difference between the SE fits and the SAID or KH80 predictions shows up in the P_{11} phases where we find a significant shift to values lower by a quarter of a degree, corresponding to a change in the phase by more than 30%. Of course, final conclusions will have to await a full phase shift analysis.

In analyses combining the cross sections for $\pi^+ p$ and $\pi^- p$ scattering, these data were used to directly determine the real part of the isospin even forward scattering amplitude, Re D^+, at $t = 0$ as a function of incident pion energy, as was done for example in the first method of Joram et al. [17]. The scattering amplitude at threshold was determined by fitting the corresponding predicted curves from phase shift analyses to the data,
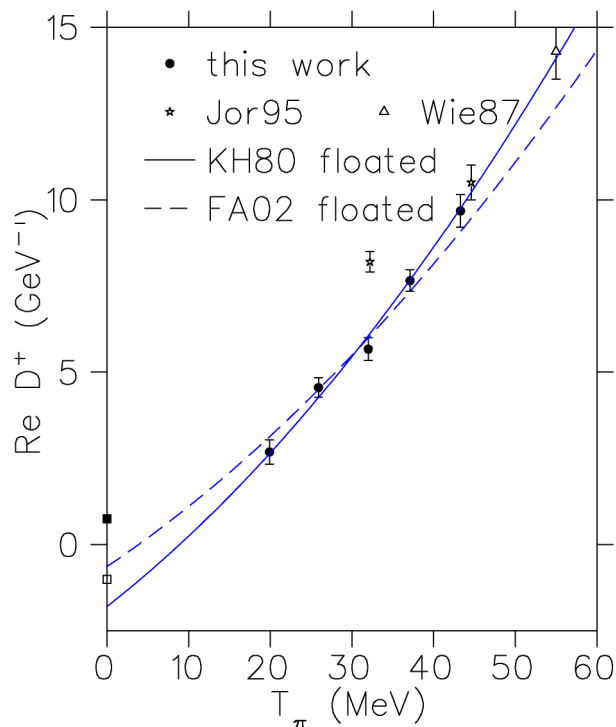
Fig. 5. Energy dependence of Re D^+. The error bars reflect statistical uncertainty of the data, the phase shift results have been renormalized to overlap the data. The original KH80 (FA02) endpoints are shown as open (closed) rectangles.

as shown in Fig. 5 compared with the predictions of KH80 and earlier data [17,23]. The a_{0+}^+ determined by fitting the KH80 results to the data is (-0.126 ± 0.010) GeV^{-1}, shifted by -0.053 GeV^{-1} from the KH80 result (solid line). The corresponding value using the functional form of FA02 (dashed line) is (-0.044 ± 0.010) GeV^{-1}, shifted by -0.093 GeV^{-1}. Although these shifted values of the scattering length correspond to a πN-sigma term at the low end of the range currently being discussed, it is very important to recognize that such extracted physics quantities are best determined through a full PSA, also making use of the complementary data available at energies above those of this work. In the low energy region the present experiment yields an extensive set of πp cross sections that almost triples the amount of pion proton cross sections. Together with the recent results on analyzing powers [21,22] and pio-

nic hydrogen [5], it provides a much expanded data base for the determination of the phase shift solutions, extraction of the scattering lengths and πN-sigma term.

Acknowledgements

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