Determination of the $\pi^{\pm}p \rightarrow \pi^{\pm}\pi^{+}n$ Cross Section Near Threshold

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The total cross section for the $\pi^{-}p \rightarrow \pi^{-}\pi^{+}n$ reaction has been measured at incident pion kinetic energies of 200, 190, 184, and 180 MeV. In addition, the $\pi^{+}p \rightarrow \pi^{+}\pi^{+}n$ reaction was measured at 200 and 184 MeV. A fit of the cross sections by *heavy baryon chiral perturbation theory* yields values of $8.5 \pm 0.6(m_{\pi}^{-3})$ and $2.5 \pm 0.1(m_{\pi}^{-3})$ for the reaction matrix elements $\mathcal{A}_{10}$ and $\mathcal{A}_{32}$, which correspond to values for the s-wave isospin-0 and isospin-2 π-π scattering lengths of $a_0 = 0.23 \pm 0.08(m_{\pi}^{-1})$ and $a_2 = -0.031 \pm 0.008(m_{\pi}^{-1})$, respectively. [S0031-9007(98)05375-7]

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Though widely successful in particle physics, QCD is notoriously difficult to apply at low energies. However, with the development of chiral perturbation theory (ChPT) which exploits the chiral symmetries of QCD [1], a means is now available for addressing low energy questions such as the determination of the strength of the simplest of the strongly interacting systems, the π-π interaction. One of the most fruitful ways of investigating this interaction experimentally has involved the measurement of threshold pion-induced pion production cross sections. Such reactions have traditionally been analyzed using the model of Olsson and Turner [2] which involves representing the π-π interaction in terms of the chiral symmetry breaking parameter ξ. In a recent publication [3], Olsson and coworkers found that the inclusion of higher-order terms, which were neglected in the earlier work, complicated the extraction of π-π scattering lengths from threshold pion production data. Subsequently, Bernard, Kaiser, and Meißner [4] used heavy baryon chiral perturbation theory (HBChPT), which incorporates the effects of higher baryon resonances, to obtain new relationships between the threshold amplitudes for pion production and the π-π scattering lengths.

The $\pi^{-}p \rightarrow \pi^{-}\pi^{+}n$ reaction involves both isospin 2 and isospin 0 π-π interaction amplitudes and the $\pi^{+}p \rightarrow \pi^{+}\pi^{+}n$ reaction involves only isospin 2. Consequently, cross-section measurements of both reactions near threshold can be used to determine both isospin amplitudes. As shown in Fig. 3(b), a consistent body of experimental data exists for the $\pi^{-}p \rightarrow \pi^{-}\pi^{+}n$ reaction at energies above 200 MeV. However, Bernard *et al.* [4] state that only data below 200 MeV can be used to extract π-π scattering lengths. The situation for the $\pi^{+}p \rightarrow \pi^{+}\pi^{+}n$ reaction, as shown in Fig. 3(a), is less satisfactory with a discrepancy of more than a factor of 2 between the data of the OMICRON collaboration [5] and that of Sevior *et al.* [6], the only two experiments for which data were obtained within 40 MeV of threshold.

Given the importance of a precise determination of the π-π scattering lengths, it is essential that near-threshold cross-section data be measured for *both* charge channels by a group other than OMICRON in order to provide a consistent set of data for extracting both isospin reaction amplitudes. To this end, the "active target" system developed by Sevior *et al.*, for the $\pi^{+}p \rightarrow \pi^{+}\pi^{+}n$ reaction [7] was adapted for the $\pi^{-}p \rightarrow \pi^{-}\pi^{+}n$ case. Although it involves a cross section which is about 10 times larger than that for the π^{+} reaction, the method has to contend with the fact that only a single positive pion occurs in the final state. This paper presents the results of measurements of $\pi^{-}p \rightarrow \pi^{-}\pi^{+}n$ cross sections at incident pion energies of 180, 184, 190, and 200 MeV, together with measurements of the $\pi^{+}p \rightarrow \pi^{+}\pi^{+}n$ cross section at 184 and 200 MeV to check the reproducibility of the previous Sevior *et al.* results [6].

The experiment was performed at TRIUMF on the M11 beam line at 200, 190, 184, 180, and 172 MeV for the negative pions and at 200, 184, and 172 MeV for the positive. In each case, the data obtained at 172 MeV provided background information, since this energy is below the threshold for the reactions of interest (172.3 MeV). The beamline was tuned for a ±0.1% spread in momenta for π^{+} and ±0.5% for π^{-}. The typical beam rates in both cases were 1.7 MHz.

The apparatus, similar to that used by Sevior *et al.* [6], is shown in Fig. 1. The beam-tracking system consisted of the three plastic scintillators. The third of these was half of the transverse size of the target, while the first

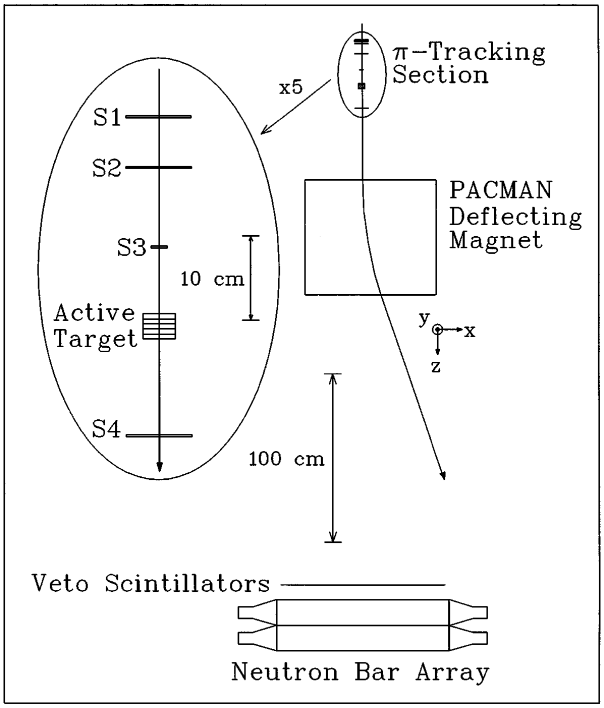

FIG. 1. Experimental layout of the apparatus.

two were large enough to detect pions from adjacent beam bursts. The active target consisted of five segments of 6 mm thick PILOT-U scintillators ($C_1H_{1.1}$) and was followed by a veto scintillator that was used to define beam interactions. Beam particles that did not interact were swept away by a dipole magnet and the neutrons were detected in an array of scintillator bars placed 3 m downstream of the target. This arrangement minimized the effects of the substantial $\pi^+C \rightarrow \pi^+nX$ background by exploiting the kinematics of the near-threshold reaction of interest, particularly the restriction of the neutrons to a narrow forward cone.

Incident pions were identified by a combination of time of flight through the M11 channel together with the amount of energy deposited in the beam-tracking scintillators. Positive pions that were produced (and stopped) in the target were identified by their signature decay $\pi^+ \rightarrow \mu^+\nu_\mu$, using three different techniques to identify and measure the height and relative time of occurrence of the pulses following the initial pion pulse in any target segment [7]. One of these techniques included the use of TRIUMF 500 MHz transient digitizers attached to the target scintillation counters.

The calibration of the pulse height response of the active target was obtained from the energy losses of 200 MeV incident π^+ which, when traversing the target, deposited 1.3 MeV per 6 mm segment. The response of the neutron bars was studied using two monoenergetic neutron reactions ($\pi^-p \rightarrow n\gamma$ and $\pi^-d \rightarrow 2n$) whose energies (8.9 and 68 MeV), spanned the expected energy range of $\pi p \rightarrow \pi\pi n$ neutrons [6].

The experimental yields were evaluated from peak areas in histograms of T_{sum}, the sum of the kinematic energies of the reaction products $T_n + \Sigma T_\pi$, which is constant for the $\pi p \rightarrow \pi\pi n$ reaction but produces a continuum for the background. The neutron kinetic energy T_n was determined from the time of flight from the active target to the detection array whereas the kinetic energy of the produced pions ΣT_π was taken as the total energy deposited in the active target.

T_{sum} spectra were accumulated with two different conditions for the π^+ channel. The first (“one π” method) required only the coincident detection of a neutron with a single stopped π^+ (and its subsequent decay) in the target. In this method, the substantial $\pi^+C \rightarrow \pi^+nX$ background was suppressed by restricting the allowed kinematic ranges for the T_π and T_n spectra. The remaining background was determined by subjecting the data at 172 MeV to the same kinematic restrictions as the T_{sum} spectra under study.

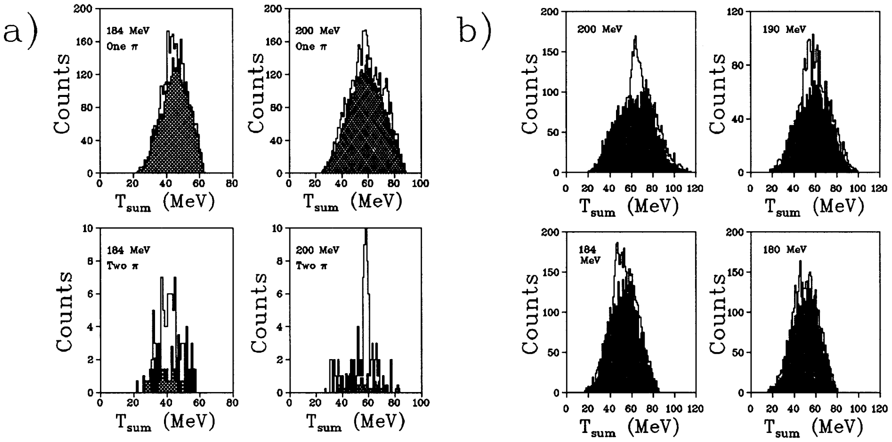

FIG. 2. T_{sum} spectra for (a) $T_\pi = 184$ and 200 MeV π^+ for both the “one π” and “two π” methods, and (b) $T_\pi = 180$, 184, 190, and 200 MeV π^- for the “one π” method.

TABLE I. Total cross sections for $\pi^{\pm} p \rightarrow \pi^{\pm}\pi^{+} n x$. The uncertainties include both statistical and systematic errors.

	Cross sections (μb)			
	$\pi^{+} p \rightarrow \pi^{+}\pi^{+} n$			$\pi^{-} p \rightarrow \pi^{-}\pi^{+} n$
T_π (MeV)	One π	Two π	Averaged	One π
200	1.4 ± 0.3	1.4 ± 0.3	1.4 ± 0.3	6.5 ± 0.9
190	⋯	⋯	⋯	3.0 ± 0.5
184	0.30 ± 0.07	0.30 ± 0.07	0.30 ± 0.07	1.9 ± 0.3
180	⋯	⋯	⋯	0.7 ± 0.1

In order to obtain the best background fit to the signal, the 172 MeV (background) spectra were scaled to the leading and trailing edges of the signal spectra. The best fits are shown together with the respective T_{sum} spectra in Fig. 2(a).

The second technique employed to extract yields ("two π" method) required the detection of two positive pions in the target, each in a different target segment. The requirement of detecting a second π^{+} substantially reduced the background. The backgrounds for this "two π" analysis were determined in similar fashion to those for the "one π" analysis. For each of the two methods, the experimental acceptances needed to enable determination of the cross sections from the measured yields were determined by Monte Carlo simulations. The results are summarized in Table I and shown in Fig. 3(a).

For the π^{-} channel, only one positive pion was present in the final state. Thus, only the first ("one π") method of analysis could be employed. Stopped negative pions are rapidly absorbed by carbon nuclei which then eject energetic fragments. However, about 50% of the time only neutral particles are emitted [8]. When this occurs the $\pi^{-} p \rightarrow \pi^{+}\pi^{-} n$ event falls in a well-defined T_{sum} peak. Such behavior was confirmed in calibration runs when negative pions from M11 were stopped in each segment of the active target in turn. The resultant pulse height distributions were used in the Monte Carlo code employed to simulate the experiment. Backgrounds for this channel were obtained at both 172 and 176 MeV. Although 176 MeV is above threshold for the $\pi^{-} p \rightarrow \pi^{+}\pi^{-} n$ reaction, the yield at this energy is negligibly small. The results obtained using the different backgrounds were the same within errors.

T_{sum} spectra from the $\pi^{-} p \rightarrow \pi^{+}\pi^{-} n$ reaction are shown in Fig. 2(b), and the cross-section results are summarized in Table I and shown in Fig. 3(b).

This experiment, like that of the OMICRON Collaboration, provides cross-section data for both π^{+} and π^{-} incident beams. These are shown in Fig. 3 along with the results of several other measurements. However, this experiment provides the only data within 8 MeV of threshold. Although the π^{-} data agree with the OMICRON results (as well as with other data sets) at the higher energies, the π^{+} data agree with the results of Sevior rather than with OMICRON. Using the formulation of Bernard *et al.* [4], our cross section data yield threshold values for the matrix elements: $|\mathcal{A}_{10}| = (8.5 \pm 0.6) m_\pi^{-3}$ and $|\mathcal{A}_{32}| = (2.5 \pm 0.1) m_\pi^{-3}$, and for the π-π scattering lengths: $a_0 = (0.23 \pm 0.08) m_\pi^{-1}$, and $a_2 = (-0.031 \pm 0.008) m_\pi^{-1}$. Our value for $|\mathcal{A}_{10}|$ is in good agreement with the value of $8.0 \pm 0.3 m_\pi^{-3}$ obtained by Bernard *et al.* [4] from an analysis of the $\pi^{-} p \rightarrow \pi^{0}\pi^{0} n$ data of Lowe *et al.* [9] and our values of the scattering lengths are consistent with the one-loop chiral

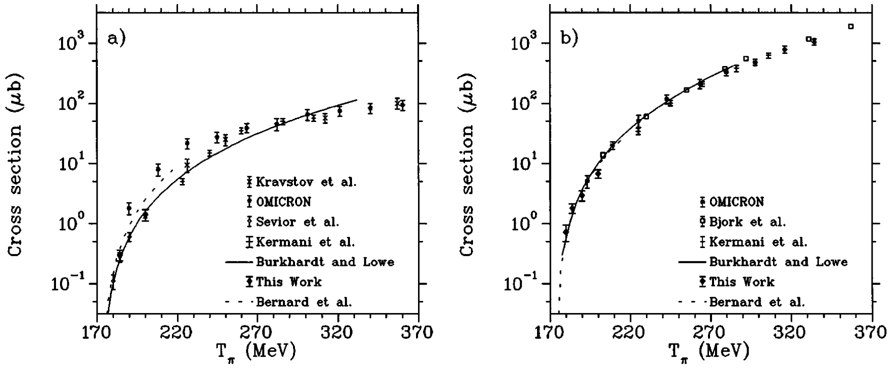

FIG. 3. Total cross section as a function of incident pion kinetic energy for (a) $\pi^{+} p \rightarrow \pi^{+}\pi^{+} n$ and (b) $\pi^{-} p \rightarrow \pi^{-}\pi^{+} n$. The data of OMICRON, Kravstov *et al.*, Sevior *et al.*, Bjork *et al.*, and Kermani *et al.* were taken from Refs. [5,6,14–17]. The solid lines are fits to previous data by Burkhardt and Lowe [18]. The dotted lines are the ChPT predictions of Bernard, Kaiser, and Meißner [4].

perturbation theory predictions of Gasser and Leutwyler [10]: $a_0 = (0.20 \pm 0.01)m_\pi^{-1}$, $a_2 = (-0.042 \pm 0.002)m_\pi^{-1}$ and the two-loop predictions of Bijnens *et al.* [11]: $a_0 = 0.2156m_\pi^{-1}$, $a_2 = -0.0409m_\pi^{-1}$, and Girlanda *et al.* [12]: $a_0 = (0.209 \pm 0.004)m_\pi^{-1}$, $a_2 = (-0.045 \pm 0.006)m_\pi^{-1}$. The uncertainties in our experimental values of the scattering lengths are dominated by the theoretical uncertainties as estimated by Bernard *et al.* [4]. Of course, the values of the scattering lengths obtained from our data are model dependent and the values thus extracted are most properly a test of HBChPT. The theoretical error quoted by Bernard *et al.* can only take account of the uncertainties within the framework of HBChPT. Nevertheless, since ChPT is embedded within HBChPT and since the π-π component of the threshold amplitude contributes 65% and 44% of the $\mathcal{A}_{10}$ and $\mathcal{A}_{32}$ amplitudes, respectively [13], our data provide a useful test of ChPT as well.

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