Physics Letters B 300 (1993) 24–28
North-Holland

PHYSICS LETTERS B

# Total cross section of the reaction $\pi^+ d \to pp$ at pion energies 26 – 40 MeV

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Received 31 August 1992; revised manuscript received 16 November 1992

Total cross sections for the reaction $\pi^+ d \to pp$ have been measured for incident pion energies $T_\pi = 26.5, 28.5, 30.5, 32.5$ and $39.5$ MeV. The data are in good agreement with previous experiments. There is some indication of a peculiarity in the energy dependence of the total cross section near incident pion energy $T_\pi = 30$ MeV.

Numerous theoretical and experimental investigations are devoted to the reaction $\pi^+ d \to pp$ and its inverse $pp \to \pi^+ d$. The study of these reactions is interesting not only for their own sake. They are main processes for pion absorption and production at intermediate energies. Understanding them is the basis for understanding the $NN$ interaction since $pp \to \pi^+ d$ is the main inelastic process in this energy region. On the other hand, we can relate the $\pi NN$ system to $\pi N$ properties because of extensive theoretical study of the two-baryon system [1]. The Faddeev approach has been successful in explaining $\pi^+ d \to pp$, $NN \to NN$, $\pi^+ d \to \pi^+ d$, and $\pi^+ d \to \pi NN$ reactions in terms of iterated $\pi N$ and $NN$ interactions, treating a set of two-baryon reactions as part of a coupled system. Also, the relative simplicity of these processes makes them attractive for the detailed examination of various dynamic microscopic models applied to nucleon–nucleus and pion–nucleus interactions as well.

In spite of a few decades of experimental and theoretical study, there are many open questions in understanding the dynamics of these reactions. A detailed discussion of the reaction $\pi^+ d \to pp$ is contained in a recent review [2]. Total and differential cross sections for the reaction $\pi^+ d \to pp$ have been measured with high accuracy at pion energies above 100 MeV. Now, the experimental efforts in this energy range mainly concern spin dependent observables. The situation at the pion energies below 100 MeV is less satisfactory especially for energies of a few tens of MeV. The complete data set on the total cross section of pion absorption on the deuteron for pion energies between 20 and 50 MeV is shown in fig. 1. The essential difference between low and high energies is that for pion energies below 50 MeV the s-wave plays a predominant role while for pion energies

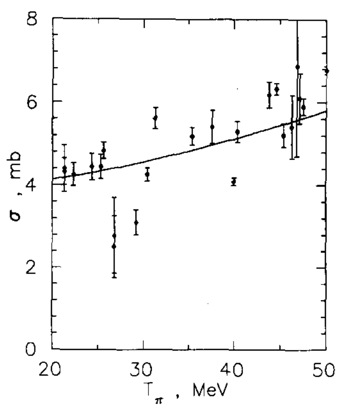


Fig. 1. Energy dependence of the total cross section for the $\pi^+ d \to pp$ reaction. Data from references contained in ref. [3]. The solid line is the parameterization from ref. [4].

above 100 MeV the effect of p-wave $\Delta$-resonance dominates the interaction. The reaction is characterized by a large momentum transfer at all energies – the momentum transfer to the nucleons is about 550 MeV/$c$. The s-wave interaction and large momentum transfer at low pion energies provide exactly the conditions for some exotic channels to manifest the non-nucleonic degrees of freedom, for example the formation of six-quark states.

We report here the results of the energy dependence measurements of the total $\pi^+d\to pp$ reaction cross section for incident pion energies between 26 and 40 MeV. The measurements were carried out at the low-energy pion channel of the St. Petersburg Nuclear Physics Institute, formerly LNPI, proton synchrocyclotron. The pion channel has a length of 8 m. The short length of the pion channel is a very important feature, especially at low pion energies. The channel has tow dipole magnets and seven quadrupole lenses, and is arranged to provide a low level of muon contamination. For the beam-content measurements, a time-of-flight system with timing relative to the radiofrequency of the accelerator was used. This procedure provides an accuracy in the determination of the pion fraction in the beam of about 1.5%. For the pion energy range from 26 to 40 MeV, the pion fraction smoothly varied from 63% to 78%. The muon contamination is approximately constant at the energy region discussed. The value of this contamination was 14% for the lowest energy and 12% for the highest one. The pion fraction decreases mainly due to the rise of the positron fraction but not the muon one. Another part of the muon contamination associated with pion decay at the last section of the channel could not be resolved by the time-of-flight measurements. Monte Carlo simulation shows that its fraction in the beam slightly depends on the beam momentum and does not exceed 1% for this pion channel [5]. The beam contents were monitored continuously during the measurements. The momentum spread of the beam depends on the slit width of a copper collimator placed at the intermediate focus of the pion channel. For these measurements, the energy spread was about 3 MeV (FWHM). A thin Si (Au) semiconductor detector placed inside the beam pipe was used for exact beam momentum determination. This technique provides an accuracy in determination of incident beam energy centroid to better than 0.5 MeV. The pion intensity was $10^3$–$10^4$ $s^{-1}$.

The experimental setup is shown in fig. 2. In consists of beam counters C1, C2 and veto counters C3, C4. C3 has a square hole $3\times3$ $cm^2$. Counters C1 and C2 are used as a beam content and flux monitor, and are combined with C3 and C4 to trigger the scintillation hodoscope-spectrometer.

The scintillation hodoscope-spectrometer has twelve plastic scintillation detectors, C5–C16, placed within a stainless-steel tank. This tank can be filled with a gas or vacuum-pumped when it is used for background measurements. The thickness of the scintillators is 10 cm, which is sufficient to stop outgoing particles originating from pion absorption. These detectors are assembled in rectangular array. Four detectors are joined in a ring surrounding the beam. There are three such identical groups located sequentially along the beam axis. The rectangular "box" formed by the scintillators' surfaces has dimensions of $10\times10\times60$ $cm^3$. When the inner volume is filled with a gas, it can be used as a target. Gaseous $H_2$ and $D_2$ targets with a pressure of 5 atm were used. This hodoscope covers a solid angle close to $4\pi$ and measures the energy of outgoing protons up to 100 MeV with a resolution of approximately 10%.

The spectrometer was calibrated using $pp$ elastic scattering. For this measurement the tank was filled with gaseous hydrogen and the pion channel was tuned to obtain a proton beam. Background measurements were carried out with an empty target.

The coincidence of signals from any two opposite walls of the hodoscope, in coincidence with the signals from beam counters C1, C2, and an absence of signals from veto counters C3, C4 was used as the trigger. Every event recorded on tape contains information about the energy deposition in each detector, time-of-flight and beam flux. The details of the ex-

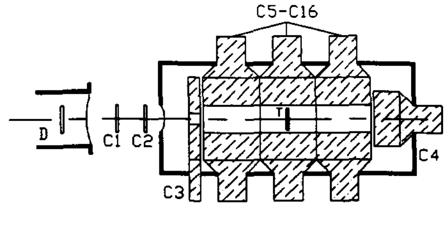


Fig. 2. Experimental setup.

perimental setup and experimental procedure are described elsewhere [6].

The measurements were made at five incident pion energies $T_{\pi}=26.5$, 28.5, 30.5, 32.5 and 39.5 MeV. Events with outgoing particles striking two opposite walls of the hodoscope-spectrometer and with the energy of each particle, namely protons, greater than 40 MeV were selected to reject events which are not related with pion absorption. For each kinematically allowed combination of hodoscope counters, the two-particle energy spectra were obtained. Different combinations of the detectors correspond to different angular intervals for outgoing particles, providing information on the angular distribution of the reaction products. However, statistics were insufficient for evaluation of the angular distribution and we extracted the total cross section only. All experimental two-proton energy spectra have a strongly pronounced peak. The peak position exactly agrees with the kinematics of the reaction. The background has been measured with an empty target. The background contribution under the peak did not exceed (8–10)% of absorption events and was subtracted. To evaluate the total cross section, we used the expression

$$\sigma_{\rm tot} = N_{\rm ev}/N_{\pi}N_{n}\epsilon\,, \qquad (1)$$

where $N_{\rm ev}$ is the integral number of events under the reaction peak for all allowed detector combinations with background subtracted, $N_{\pi}$ is the total number of incident pions, $N_n$ is the effective number of nuclei in a gas target, and $\epsilon$ is a factor accounting for the acceptance and efficiency of the experimental setup. Certainly, this factor depends on the geometry of the setup and the angular distribution of outgoing particles. To calculate $\epsilon$, a Monte Carlo simulation has been done. These calculations accounted for geometry of the setup, pion decay in the target volume, and detector thresholds. We used the parameterization of the angular distribution for the reaction $\pi^{+}d\to pp$ from ref. [4] in the simulation. The FOWL [7] phase space generator has been used.

The total cross sections determined in this experiment are given in table 1. The uncertainties are statistical.

To test the self-consistency of the data, a total cross section has been evaluated for each detector combination separately using the above described procedure. To do this, partial values of $\epsilon$ for particular combinations were calculated. The total cross section values extracted from different combinations agree with each other within the accuracy of measurement. This fact demonstrates the correctness of our calculations of $\epsilon$.

Table 1
Total cross section for the reaction $\pi^{+}d\to pp$.

| $T_{\pi}$ (MeV) | $\sigma_{\rm tot}$ (mb) |
|---|---|
| 26.5 | $4.94\pm0.26$ |
| 28.5 | $5.49\pm0.28$ |
| 30.5 | $4.49\pm0.27$ |
| 32.5 | $5.58\pm0.26$ |
| 39.5 | $5.35\pm0.24$ |

An analysis of systematic errors in the absolute normalization shows three main sources, namely incident pion flux determination, effective number of target nuclei and efficiency of the experimental setup. The last two are coupled and were determined using simulation. A gas pressure in a target was monitored continuously during measurements and was constant within an accuracy better than 1%. Our estimate shows that overall systematic uncertainty in absolute normalization is less than 8%, whereas relative normalization uncertainty between different points in incident energy is much smaller and does not exceed 2%. The latter uncertainty is mainly connected with the accuracy of incident flux determination.

Direct measurements, with a good statistical accuracy of (2–3)%, were carried out by Ritchie et al. for pion energies of 20–65 MeV [8] and 4–20 MeV [9]. Other data, in the same energy range (16–69 MeV) and for a narrower angular interval, have been reported by Mathie et al. [10] for the inverse reaction at proton energies of 305–425 MeV. That experiment has an accuracy of about 5%. In spite of small reported errors in both experiments, there is a rather large (about 25%) discrepancy between them. In the experiments of Ritchie et al. the total cross section measurements were carried out for $T_{\pi}=20$–45 MeV with an energy step of 5 MeV. The possible presence of a peculiarity in the energy dependence nearby $T_{\pi}=30$ MeV attracts ones attention. The total cross section at 30.4 MeV is $4.26\pm0.16$ mb, while for the adjacent energies 25.3 and 35.4 MeV it is $4.84\pm0.20$ and $5.19\pm0.21$ mb, respectively. It is interesting that other experiments (fig. 1) show deviation from a smooth energy dependence at approximately the same energy, which corresponds to an invariant mass of 2.04 GeV. It should also be mentioned that the energy dependence of the total cross section for the *pp* triplet state with projection of spin equal zero with respect to the beam axis $\sigma_{T0}=\sigma_{tot}+\frac{1}{2}\Delta\sigma_L-\Delta\sigma_T$, where $\Delta\sigma_L=\sigma(\rightleftarrows)-\sigma(\rightrightarrows)$ and $\Delta\sigma_T=\sigma(\uparrow\downarrow)-\sigma(\uparrow\uparrow)$ are the differences of the total *pp* cross sections in pure spin states, shows the structure of the same order as the dip in fig. 1 (for a detailed discussion see ref. [6]).

It is intriguing that in a recent experiment on pion absorption on carbon by Akimov et al. [6], a dip in the energy dependence of the quasi-deuteron component of absorption near $T_\pi=28$ MeV has been observed. Some possible, alternative non-conventional interpretations of this peculiarity have been advanced in ref. [6]. In the particular case of absorption on deuterons, one of them could be applicable. These structures, if they exist, could be caused by a diproton resonance in the $^3P_2$ *NN* channel. A different result for carbon has been recently published by Jones et al. [11]. The energy dependence of the $^{12}C(\pi^+, 2p)$ total cross section was studied at energies from 19 to 140 MeV. The laboratory angular distribution for this reaction was fitted with a Legendre polynomial series,

$$\frac{d\sigma}{d\Omega}=a_0+a_1P_1(\cos\theta)+a_2P_2(\cos\theta)\ . \qquad (2)$$

These measurements show a smooth energy dependence of the cross section without any structure at $T_\pi=28$ MeV. A hint of a 5 MeV wide bump near $T_\pi=24$ MeV is seen in the $a_2$ energy dependence. It is known that the *A*-dependence of the total absorption cross section is $\sigma\sim A^{0.5-0.7}$ and the exponent decreases with increasing energy [12]. As a result, the slope of the energy dependence of the total cross section should be decreasing for heavier nuclei. The quoted data of Jones et al. are in contradiction with this behavior since the energy dependence for $^{12}C(\pi^+, 2p)$ obtained in their experiment is much steeper than for $\pi^+d\to pp$. At the same time, the data of Akimov et al. [6] agree with the dependence for the $\pi^+d\to pp$ reaction. A discrepancy between the two referred experiments (ref. [6] and ref. [11]) could be explained by a difference in data analysis procedure and event selection criteria [13,14]. The systematic accuracy of data by Akimov et al. for a carbon target is better than in the experiment by Jones et al., thus these data do not disprove the existence of the structure under discussion.

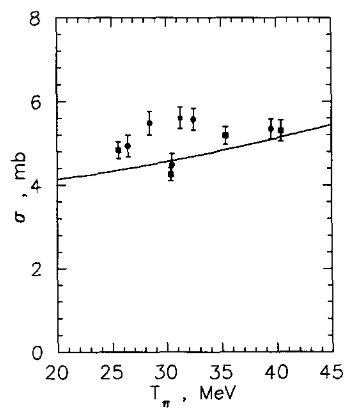


Fig. 3. Total cross section for the $\pi^+d\to pp$ reaction. The circles are data from this experiment, the squares are data from ref. [8], the stars are data from ref. [10]. The solid line is the parameterization from ref. [4].

The measured energy dependence of the total cross section is shown in fig. 3. The data from ref. [8] and ref. [10] are presented in the same plot. The solid line is the parameterization from ref. [4]. We point out that the data shown for the three experiments do seem to indicate the presence of a narrow structure near an incident pion energy of 30 MeV. A better determination will require measurements with smaller step in incident energy, which we plan to do.

It is a pleasure to acknowledge valuable discussion with M.G. Ryskin, B.G. Ritchie, E.W. Vogt, C.L. Morris, M.K. Jones, S.J. Green, and to thank L.M. Kochenda and A.V. Shishkov for their assistance in data taking.

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