Observation of strong final-state effects in $\pi^+$ production in pp collisions at 400 MeV

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Differential cross sections of the reactions $pp \rightarrow d\pi^+$ and $pp \rightarrow pn\pi^+$ have been measured at $T_p = 400$ MeV by detecting the charged ejectiles in the angular range $4^0 \leq \Theta_{Lab} \leq 21^\circ$. The deduced total cross sections agree well with those published previously for neighbouring energies. The invariant mass spectra are observed to be strongly affected by $\Delta$ production and $NN$ final-state interaction. The data are well described by Monte Carlo simulations including both these effects. The ratio of $pp \rightarrow pn\pi^+$ and $pp \rightarrow d\pi^+$ cross sections also compares favourably to a recent theoretical prediction which suggests a dominance of $np$-production in the relative $^3S_1$-state.
The single pion production has received renewed interest in recent years both from experimental and theoretical points of view. Theoretical aspects currently under discussion include possible heavy meson exchange, the nature of the $\pi NN$ vertex and the role of final-state interactions (FSI) in these reactions. Experimentally the availability of storage rings has opened the possibility to measure single pion production with high statistics even close to threshold \[1,2,3,4\]. These data show an energy dependence of the total cross section near threshold, which deviates substantially from phase space suggesting a strong influence of the $NN$ FSI. In this Letter we show that FSI effects can be explicitly observed and identified in the invariant ($M$) and missing mass ($MM$) spectra of the reaction $pp \rightarrow pn\pi^+$. The energy of $T_p = 400$ MeV is already high enough for $\Delta$-production to be observed clearly in $M_{n\pi^+}$ and $M_{p\pi^+}$, whereas the $pn$ FSI still strongly influences $M_{pn}$ even though this energy is well above threshold.

The measurements have been performed at the CELSIUS storage ring at $T_p = 400$ MeV using the WASA/PROMICE detector setup including a hydrogen cluster jet target. Details of the detector and its performance are given in \[5\]. For the data presented here only the forward detector has been utilized, which allows the determination of the four-momentum of charged particles in the angular range of $4^\circ \leq \Theta_{Lab} \leq 21^\circ$. It is composed of a tracker with proportional counter straw chambers for an accurate determination of particle trajectories, followed by segmented scintillator trigger and range hodoscopes for dE and E determinations, respectively. Particle identification has been made by use of the dE-E method. Fig. 1 shows a three-dimensional plot of the dE-E spectrum. Deuterons, protons and pions appear well separated. For the $\pi^+$ identification the delayed pulse technique (observation of the delayed pulse from $\mu^+$ decay following the $\pi^+$ decay) has been utilized in addition. Though protons and deuterons appear to be well separated in Fig. 1, their separation is not perfect and the contamination of reconstructed $pn\pi^+$ events with $d\pi^+$ events, and vice versa, is non-negligible. In order to get rid of this contamination we have requested the $d\pi^+$ events to be planar ($\Delta\Phi = 170^\circ - 190^\circ$) and the $p\pi^+$ events to be non-planar. This way mutual contaminations could be kept below 1%. The final number of good events which passed all
criteria has been about $10^5$ for $d\pi^+$ and $7 \times 10^4$ for $pn\pi^+$. The integral luminosity has been determined to better than 5\% by the simultaneous measurement of $pp$ elastic scattering and its comparison to literature values [7]. Detector response and efficiencies have been determined by Monte-Carlo (MC) simulations, utilizing the program package GEANT [8] including the treatment of secondary interactions in the detector.

The data obtained for $pp \rightarrow d\pi^+$ are shown in Fig. 2. In the upper part the $\pi^+$ missing mass $MM_{\pi^+}$ which gives a peak at the position of the deuteron mass is displayed together with the corresponding MC simulations. The good agreement demonstrates that the detector response is understood to high precision. The measured $\pi^+$ angular distribution in the center-of-mass (c.m.) system is displayed in the lower part of Fig. 2 together with the SAID phase shift prediction [7]. Note that the angular distribution is symmetric about 90° due to the symmetry in the entrance channel. The limited angular range of the data results from the experimental requirements of $4^\circ \leq \Theta_{Lab} \leq 21^\circ$ for both $d$ and $\pi^+$. The experimental points are compatible with SAID, and we may use the angular dependence of the latter to extrapolate our data to $4\pi$. This way we obtain a total cross section $\sigma(pp \rightarrow d\pi^+) = 0.78 \text{ mb}$, which compares quite favorably with the SAID value of 0.82 mb. Whereas the statistical uncertainty is less than 1\%, the systematic uncertainty is estimated to be about 7\% comprising uncertainties both from the determination of the luminosity and from the handling of deuteron breakup in the detector by the MC simulation.

Results for the $pp \rightarrow pn\pi^+$ reaction are comprised in Figs. 3–5. The invariant and missing mass spectra reconstructed from the measured $p\pi^+$ events are shown in Fig. 3 together with curves from MC simulations assuming pure phase space (dotted) and including either $\Delta^{++}(\Delta^+)$ excitation in the $p\pi^+(n\pi^+)$ system (dash-dotted) or the s-wave FSI in the $pn$ system (dashed). For the latter the effective range approximation of Migdal-Watson type as given in [8] has been used. The only free parameter, $R$, accounts for the size of the interaction region, from which the two nucleons emerge, and effectively subsumes also the part of the reaction, where the two nucleons are not in relative s-waves. For a point-like vertex one finds $R \approx 0.8 \text{ fm}$ [3]. Here in the MC simulations $R$ has been adjusted for best
reproduction of the data resulting in $R = 2.5$ fm, if we assume the s-wave $pn$ system to be in pure $^3S_1$ states as previous work suggests \cite{9,10}. This assumption will also be corroborated by a comparison of the $d\pi^+$ and $pn\pi^+$ channels below. The value for $R$ is compatible with those obtained in analyses of the $NN$ FSI in the deuteron breakup on the proton at low energies \cite{11}. The $\Delta$ excitation in the exit channel is assumed to take place between the $\pi^+$ and either the proton or the neutron according to the isospin ratio of 9 : 1 with the $\pi^+$ being in relative p-state in the $\pi N$ system. Note that parity conservation requires the pion also to be in a $p$-wave relative to $^3S_1$ $pn$ final state.

The MC simulation including both FSI effects together is displayed in Fig. 3 by the shaded histograms which reproduce the data very well. The invariant mass spectrum $M_{p\pi^+}$ and the missing mass spectrum $MM_p$ (corresponding to $M_{n\pi^+}$) are peaked towards large masses, whereas $MM_{\pi^+}$ (corresponding to $M_{pn}$) is strongly peaked towards low masses in contrast to phase space distributions (dotted lines). In all three spectra both FSI effects play a significant role. However, the fact that the peaking towards large masses is much more pronounced in $M_{p\pi^+}$ than in $MM_p$, clearly exhibits a strong influence of the $\Delta$ production, since it is nine times more likely in the $p\pi^+$ system than in the $n\pi^+$ system. This observation in $M_{p\pi^+}$ and $M_{n\pi^+}$ is strongly different from the one at $T_p = 310$ MeV, where both spectra have been observed to be of comparable shape \cite{1}. However, it is in agreement with the trend observed for $T_p \leq 330$ MeV \cite{2}. From the partial-wave analysis of those data it was found \cite{2} that the resonant $p$-wave contribution, though still small at these energies, is steeply rising with incident energy. From this analysis the $\Delta$ contribution is expected to get dominant at energies of $T_p \approx 400$ MeV (see Fig. 20 of Ref. \cite{2}). This is indeed what we observe in our data. We note that the strong influence of the FSI on the pion energy distribution is already apparent in the dE-E plot in Fig. 1, where the pions of the $pn\pi^+$ reaction are seen to be concentrated towards the peak of the $d\pi^+$ reaction.

In Fig. 4 the experimental pion and proton angular distributions, corrected for detector efficiency and acceptance, are compared to MC simulations for the reaction $pp \rightarrow pn\pi^+$. As in $pp \rightarrow d\pi^+$ the angular distributions have to be symmetric about 90°. The proton
angular distribution is essentially isotropic being affected only slightly by the $\Delta$ excitation. The pion angular distribution, on the other hand, depends strongly on the $\Delta$ excitation. Conventionally the pion angular distributions in single pion production are parametrized by $\sigma(\Theta_\pi) \sim 1/3 + b \cos^2 \Theta_\pi$, where $b$ is the so-called anisotropy parameter. Previous analyses yielded values for $b$ up to 0.5 for $np \rightarrow nn\pi^+$ [12] and 0.3 for $pp \rightarrow pp\pi^0$ [13] with the maximum $b$ being reached near $T_p \approx 550$ MeV. The $b$ values are observed to decrease with decreasing $T_p$. At $T_p = 460$ MeV, the lowest energy analyzed in those studies, $b$ gets as small as 0.1. On the other hand the IUCF measurements [1,2] of $pp \rightarrow pn\pi^+$ show a strong rise of $b$ already close to threshold reaching $b = 0.23(6)$ at their highest energy of $T_p = 330$ MeV. Whereas from the latter we would expect to find already a quite substantial value of $b$ at 400 MeV, the previous analyses would suggest rather a small value. Hence we show in Fig. 4 two MC calculations including $pn$ FSI and $\Delta$ excitation, one with $b = 0.1$ (dashed lines) and one with $b = 0.4$ (solid) — in addition to the phase-space expectation (dotted line). In the measured range of $\Theta_\pi$ the data clearly prefer the larger $b$ value. From the $\cos^2(\Theta_\pi)$ plot of the pion angular distribution in Fig. 4 it is readily seen that $b = 0.7$ would be an upper limit compatible with our data. For a more precise determination of $b$ larger pion angles are necessary, which are not covered by this measurement. Hence also the determination of the total cross section from our data is not independent of the assumption for $b$. Whereas for $b = 0.1$ one would obtain a value of $\sigma(pp \rightarrow pn\pi^+) = 0.73(4)$ mb, our data favour values of 0.62(4) and 0.57(4) mb for $b = 0.4$ and 0.7, respectively, where the assigned uncertainty is essentially due to that of the luminosity. The latter values are in good agreement with literature values at neighbouring energies (see [1]).

The close relation between $d\pi^+$ channel and $pn\pi^+$ channel as the breakup channel of the former has recently been pointed out by Boudard, Fäldt and Wilkin [9]. Assuming that the final $pn$ system is in the $^3S_1$ state, and that the pion production operator is of short range, they derive a simple relation (eq. 6 of ref. [9]) for the ratio of differential cross sections
defined by

\[ R(Q) = 2\pi B_d \frac{d^2\sigma}{d\Omega_\pi dQ} (pp \to pn\pi^+)/\frac{d\sigma}{d\Omega_\pi} (pp \to d\pi^+) = \frac{p(x)}{p(-1)} \sqrt{x} \]

which should be independent of the pion scattering angle. Here \( B_d \) denotes the deuteron binding energy and \( Q = M_{pn} - m_d \) the excitation energy in the \( pn \) system, \( x = Q/B_d \) and \( p(x) \) is the pion c.m. momentum. Our experimental result for \( R(Q) \) is plotted in Fig. 5 together with the prediction of Ref. [9]. Though there is good qualitative agreement, the data exhibit a significantly steeper slope than the prediction. In particular, the data are higher at low \( Q \), where the approximations made in Ref. [9] should be valid best. Experimentally the determination of \( R(Q) \) from the simultaneous measurement of both reactions is expected to be particularly reliable, since uncertainties in the determination of the luminosity and detector response cancel to large degree in the ratio, the only major source of possible error being the treatment of the deuteron breakup in the detector. However, since our result for \( \sigma(pp \to d\pi^+) \) agrees well with the literature values at neighbouring energies, we do not see a significant problem there either. A closer inspection of Fig. 1 in ref. [9] indicates that experimentally \( R(Q) \) is not fully angle independent. The TRIUMF data [10] plotted there exhibit a systematic trend around the maximum of \( R(Q) \): the data taken at small angles \( (\Theta_{Lab} = 46^\circ, 56^\circ) \) lie systematically above the theoretical curve, whereas the ones taken at larger angles \( (73^\circ - 88^\circ) \) lie significantly below. Our result for the forward angular range fits very well into this trend in the TRIUMF data. Since in the calculation of \( R(Q) \) only the isoscalar \( ^3S_1 \) channel of the \( pn \) system is considered, the surplus of approximately 10% in our data at small \( Q \) may be associated with contributions from other partial wave channels, notably the \( ^1S_0 \) channel of the \( pn \) system. This conclusion conforms quite nicely with the expectations from the partial-wave analysis at lower energies [2]. The observed discrepancy between calculation and data at higher \( Q \) may be associated with effects from higher partial waves as well as with kinematic approximations made in the derivation of the theoretical expression for \( R(Q) \) [9].

Summarizing we observe in the exclusive measurement of \( pp \to pn\pi^+ \) at \( T_p = 400 \text{ MeV} \)
strong FSI effects in the invariant and missing mass spectra which are identified as being
due to $pn$ FSI and $\pi N\Delta$ excitation. The dominance of the latter is in agreement with
expectations from partial-wave analyses close to threshold. The influence of the former is
in agreement with expectations for the Migdal-Watson effect in the $pn$ system, if $s$-waves
are dominating there. The observed ratio $R(Q)$ for the exit channels $pn\pi^+$ and $d\pi^+$ is
compared with the prediction of ref. [9] relating the channel of the bound system with its
breakup channel. Although the general agreement is good, there are significant differences
which call for a more refined theoretical treatment of both channels.

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REFERENCES

[1] J.G. Hardie et al., Phys. Rev. C56, 20 (1997)

[2] R.W. Flammang et al., Phys. Rev. C58, 916 (1998)

[3] A. Bondar et al., Phys. Lett. B356, 8 (1995)

[4] H.O. Meyer et al., Phys. Rev. Lett. 65, 2846 (1990 and Nucl. Phys. A539, 633 (1992)

[5] H. Calen et al., Nucl. Instr. Meth. A379, 57 (1996)

[6] program package GEANT, CERN library

[7] program package SAID; Chang Heon Oh, R. Arndt, I. Strakovsky, R. Workman, Phys. Rev. C56, 635 (1997)

[8] M. Schepkin, O. Zaboronski, H. Clement, Z. Phys. A345, 407 (1993)

[9] A. Boudard, G. Fäldt, C. Wilkin, Phys. Lett. B389, 440 (1996)

[10] W.R. Falk et al., Phys. Rev. C32, 1972 (1985)

[11] H. Brückmann et al., Phys. Lett. B30, 460 (1969)

[12] A. Bannwarth et al., Nucl. Phys. A567, 761 (1994)

[13] G. Rappenecker et al., Nucl. Phys. A590, 763 (1995)
FIGURES

FIG. 1. Plot of the dE-E spectrum for two charged particles in the forward detector (FD). The energy loss dE has been measured by the forward trigger hodoscope (FTH), see ref. [5]. Energies are given in units of GeV.

FIG. 2. Top: Spectrum of the π⁺ missing mass MM₁⁺ as obtained from identified dπ⁺ events together with the corresponding MC simulation (shaded area) of the detector response. Bottom: Measured π⁺ angular distribution for pp → dπ⁺ in comparison with the SAID phase shift prediction [7].

FIG. 3. Spectra for pπ⁺ invariant mass M_pπ⁺ and missing masses MM_p and MM₁⁺ for pp → pnπ⁺ reconstructed from the pπ⁺ events detected for 4° ≤ Θ_Lab ≤ 21°. Corresponding MC simulations are shown assuming pure phase space (dotted), including either pn FSI (dashed) or Δ excitation (dash-dotted) and both together (shaded histograms).

FIG. 4. Angular distributions of protons (top) and pions (bottom) for pp → pnπ⁺ reconstructed from the detected pπ⁺ events. They are plotted in dependence of cos²(Θ) and are compared to MC simulations assuming pure phase space (dotted) and including both pn FSI and Δ excitation with b = 0.1 (dashed) or b = 0.4 (solid). All simulations are normalized to an integral cross section of σ = 0.62 mb.

FIG. 5. Ratio R(Q) of the pp → pnπ⁺ and pp → dπ⁺ differential cross sections. The solid curve shows the prediction of Ref. [8].
Fig. 1
\[ p p \rightarrow d \pi^+ \]

**Fig. 2**
**Fig. 3**

The figure shows the production cross sections for different systems:
- $p p \rightarrow p n \pi^+$
- $M_{p\pi^+}$
- $MM_p$

Each plot displays the cross section in units of $mb/GeV$ as a function of $GeV$.
$p \ p \rightarrow \ p \ n \ \pi^+$

\[ \sigma (\Theta_p) \text{ [\mu b / sr]} \]

\[ \sigma (\Theta_\pi) \text{ [\mu b / sr]} \]

**Fig. 4**
Fig. 5