Differential cross section and analysing power of the quasi-free $pn \rightarrow \{pp\}_s \pi^-$ reaction at 353 MeV

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Abstract

In order to establish links between $p$-wave pion production in nucleon-nucleon collisions and low energy three-nucleon scattering, an extensive programme of experiments on pion production is currently underway at COSY-ANKE. The final proton pair is measured at very low excitation energy, leading to an $S$-wave diproton, denoted here as $\{pp\}_s$. By using a deuterium target we have obtained data on the differential cross section and analysing power of the quasi-free $\vec{p}n \rightarrow \{pp\}_s \pi^-$ reaction at 353 MeV. The spectator proton $p_{sp}$ was either measured directly in silicon tracking telescopes or reconstructed using the momentum of a detected $\pi^-$. Both observables can be described in terms of $s$-, $p$-, and $d$-wave pion production amplitudes. Taken together with the analogous data on the $\bar{p}p \rightarrow \{pp\}_{s} \pi^0$ reaction, full partial wave decompositions of both processes were carried out.

Key words: Negative pion production; Neutron proton collisions; Amplitude analysis
PACS: 13.75.-n, 14.40.Be, 25.40.Qa

There is an extensive programme of near-threshold measurements of $NN \rightarrow \{pp\}_s \pi$ at the COSY-ANKE facility of the Forschungszentrum Jülich [1,2]. Here the $\{pp\}_s$ denotes a proton-proton system with very low excitation energy, $E_{pp}$, which is overwhelmingly in the $^1S_0$ state with antiparallel proton spins. The primary aim of these experiments is to carry out a full amplitude analysis which would lead to a determination of the pion $p$-wave production strength from the $^3S_1$ initial state that could provide links with other intermediate energy phenomena. As part of this programme, we have already presented data on the cross section and analysing power of the $\bar{p}p \rightarrow \{pp\}_{s} \pi^0$ reaction, which can be described in terms of $s$- and $d$-wave pion production amplitudes [3]. We here present analogous results for the quasi-free $\bar{p}n \rightarrow \{pp\}_s \pi^-$ reaction at an effective beam energy around 353 MeV.

In the absence of an intense monochromatic neutron beam, the study of the $pn \rightarrow \{pp\}_s \pi^-$ reaction is most eas-

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illy carried out through quasi-free $\pi^-$ production, with a proton beam incident on a deuterium target. In order to make a full reconstruction of a $pd \rightarrow p_{sp}\{pp\},\pi^-$ event, it is necessary to measure accurately the momentum of three of the particles in the final state. Determinations have been made at TRIUMF of both the cross section [4] and proton analysing power [5] by detecting the pion together with the two fast protons. The spectator proton, $p_{sp}$, was then identified through the missing mass in the reaction and its momentum reconstructed kinematically. Data were taken for three beam energies, though only in the central region of pion angles. The lowest of these energies was 353 MeV and, to allow a close comparison, we have concentrated our attention on this energy.

In contrast to the TRIUMF data, we have extended the coverage to the whole angular domain, which is very important in the subsequent partial wave analysis. Furthermore, by including the possibility of detecting directly the spectator proton or the $\pi^-$, we have obtained an independent check on some of the systematics involved.

The circulating proton beam was polarised perpendicularly to the horizontal plane of the machine and the polarisation reversed in direction every six minutes. The CM energy of the quasi-free $pn$ system depends on the energy and the emission angle of the spectator and for this experiment the effective “free” beam energy was in the range $T_{\text{free}} \approx (310–390) \text{ MeV}$. However, for the reconstructed events, $T_{\text{free}}$ was measured with an accuracy of $\sigma(T_{\text{free}}) = 2–4 \text{ MeV}$ and only data in the range $T_{\text{free}} = 353 \pm 20 \text{ MeV}$ were used in the analysis.

The identification of the $pd \rightarrow p_{sp}\{pp\},\pi^-$ reaction starts from the selection of pairs of fast protons through the difference between their times of flights in ANKE [11]. Since the beam energy is quite low, other pairs of particles gave a negligible contribution to the background, which originated mostly from accidental coincidences, and amounted to $\lesssim 7\%$. To select the $\Sigma_0$ diproton state, we imposed a $E_{pp} < 3 \text{ MeV}$ cut on the data, which could be done reliably because of the excellent resolution of $\sigma(E_{pp}) < 0.6 \text{ MeV}$. It is important to note that the identical cut was placed on the $pp \rightarrow \{pp\},\pi^0$ data [3], which is important when considering the relative normalisation uncertainties for $\pi^0$ and $\pi^-$ production.

The time-of-flight criterion was also used to select the $\pi^-$ in the ND, where the very low background consisted only of...
accidentals and strongly scattered positively charged particles. The background level for the spectator protons identified in the STT was at the 5–8% level, depending on the proton energy and angle.

Having measured three of the final particles, the residual one from the $pd \rightarrow psp\{pp\},\pi^−$ reaction was identified by the missing-mass method. This is illustrated separately in Fig. 2 for the cases where the spectator proton or $\pi^−$ was detected. The main backgrounds were from accidental coincidences, which were particularly significant for spectator protons because no timing information from the STT was used in the analysis. The shape of this background was derived from artificially constructed events. The momenta of the fast protons were taken from the experimental events where neither a spectator proton nor $\pi^−$ was detected, to which was added a random spectator momentum taken from the sample acquired with the STT trigger. The missing-mass spectrum was then fitted with the sum of this background distribution and a Gaussian. The background level was estimated separately for each detector combination, spin orientation of the beam, and angular bin. Any uncertainties here were combined with the statistical errors.

In order to estimate the resolutions and acceptance of the system, a full simulation of the ANKE setup was performed [11], based on the GEANT package [12]. The acceptance was calculated as a function of $θ_π$ for both the $π^−$ and spectator proton detection, assuming that the spectator was emitted isotropically, with the energy being sampled from the Fermi distribution [13]. The fast proton pair was generated in the $^1S_0$ state, with the distribution in excitation energy being weighted by the Migdal-Watson factor [14] that included the Coulomb interaction [15].

The polarisation of the proton beam and the luminosity were both estimated from quasi-free $\vec{p}π^− \rightarrow dπ^0$ data that were taken in parallel. The fast deuteron was detected in the FD, and selected by its energy loss in the counters, and the spectator proton measured in coincidence in the STT. The reaction was then identified by the missing-mass method. The measurements of both the analysing power and cross section depend sensitively on the relative luminosities for the two spin states and this was controlled by comparing the rates of ejectiles emitted at $θ = 0°$ or $φ = ±90°$, which cannot depend upon the beam polarisation. Using calibration data taken from the SAID database [16], the integrated luminosity was found to be $L = (2310 ± 110)$ nb$^{-1}$. No correction was made for the shadowing in the deuteron since there is a similar effect in the measurement of the quasi-free $pn \rightarrow \{pp\},\pi^−$ rate. The beam polarisation determined in this way was $P = 0.66 ± 0.06$. This is consistent with that found in the $\pi^0$ production experiment [17] that was undertaken with the same conditions just before the $\pi^−$ run. The luminosities in the two polarisation states were on average very close, $L_1/L_2 = 1.017 ± 0.005$.

Figure 3 shows the differential cross-section $dσ/dΩ$ for the quasi-free $pn \rightarrow \{pp\},\pi^−$ reaction integrated over the $E_{pp} = (0−3)$ MeV range of $pp$ excitation energies and averaged over the effective beam energy $T_{beam} = 353 ± 20$ MeV. The data were extracted within the impulse approximation model, where the weighting of the spectator momentum distribution was taken from the Bonn deuteron wave function [17], though the result was insensitive to this choice. The cross-section was estimated separately for $\pi^−$ and spectator proton detection and, since these two results were found to be consistent, only their weighted average is presented. Also shown are the TRIUMF data on quasi-free $\pi^−$ production [4]. They imposed a slightly more severe $E_{pp}$ cut on their data and these were converted to our 3 MeV cut by assuming a Migdal-Watson energy variation [14].

Whereas the TRIUMF results only cover the central region of pion angles [4], the current data extend over the whole angular domain. The two data sets are consistent in the backward hemisphere but the TRIUMF measurements show no indication of the rise at forward angles that is seen at ANKE. Some confirmation of the ANKE angular shape is offered by pion absorption data, $\pi^−\bar{^3}He \rightarrow pnn_{sp}$, where the unobserved slow neutron is assumed to be a spectator [18]. In this case the reaction can be interpreted as being $\pi^−\{pp\}_s \rightarrow pn$, though the internal structure of the diproton is very different to that in the production data. Over the range of angles covered, our data are completely consistent with these absorption results. The forward/backward peaking is in complete contrast to the results found for $\pi^0$ production [20,3] and is an indication of the dominance of the $I = 0$ $p$-wave amplitudes in this reaction.

The unpolarised cross section for $\pi^−$ production, and this time the proton analysing power $A_y$, must be of the form

$$
\frac{dσ}{dΩ} = \frac{k}{4π} \sum_{n=0}^∞ a_n \cos^n θ_π, \tag{1}
$$

$$
A_y \left( \frac{dσ}{dΩ} \right) = \frac{k}{4π} \sin θ_π \sum_{n=0}^∞ b_{n+1} \cos^n θ_π, \tag{2}
$$

Fig. 2. Kinematic identification of the $pd \rightarrow psp\{pp\},\pi^−$ reaction. a) Sample of missing-mass squared data from events where the spectator proton is detected, showing the experimental spectrum (with error bars), the background (shaded area), and the sum of this plus a Gaussian for the $\pi^−$ peak (solid curve). b) Missing-mass distribution when the $\pi^−$ is detected. The curve shows the fit to the experimental data with the sum of a Gaussian centred on the mass of the proton and a linear background.
reaction are displayed in Fig. 4, with $A_y(d\sigma/d\Omega)$ being shown in panel a and $A_y$ in panel b. The agreement with the TRIUMF $A_y$ data [5] is reasonable at large angles and both show the strong and rather asymmetric oscillation in the central region. However, there are clear discrepancies for $\theta_\pi \lesssim 60^\circ$, as there are also for the cross section shown in Fig. 3.

where $\theta_\pi$ is the pion c.m. production angle with respect to the direction of the polarised proton beam. Here $p$ is the incident c.m. momentum and $k$ that of the produced pion. We are neglecting here any small effects due to the mass differences and at 353 MeV; the momenta then have values $p = 407$ MeV/c and $k \approx 94$ MeV/c. The best fits of Eq. (1) to the differential cross section are found with the parameters quoted in Table 1.

| Observable | Direct fit | Global fit |
|------------|------------|------------|
| $a_0(pp)$  | $4.05 \pm 0.08$ | $4.05 \pm 0.08$ |
| $a_2(pp)$  | $-2.31 \pm 0.14$ | $-2.34 \pm 0.14$ |
| $b_2(pp)$  | $1.82 \pm 0.10$  | $1.80 \pm 0.10$  |
| $a_0(nn)$  | $2.69 \pm 0.18$  | $2.47 \pm 0.08$  |
| $a_1(nn)$  | $-8.24 \pm 0.51$ | $-7.83 \pm 0.45$ |
| $a_2(nn)$  | $9.11 \pm 0.70$  | $10.12 \pm 0.41$ |
| $a_3(nn)$  | $2.89 \pm 0.90$  | $1.38 \pm 0.27$  |
| $b_1(nn)$  | $1.77 \pm 0.14$  | $1.82 \pm 0.13$  |
| $b_2(nn)$  | $-1.95 \pm 0.50$ | $-1.75 \pm 0.36$ |
| $b_3(nn)$  | $-4.43 \pm 0.70$ | $-4.83 \pm 0.27$ |

Table 1

Values of the parameters in $\mu b/sr$ extracted by direct fits of Eqs. (1) and (2) to the $pp \rightarrow \{pp\}_s, \pi^0$ and $pn \rightarrow \{pp\}_s, \pi^-$ experimental data and those obtained on the basis of Eq. (5) from the amplitudes given in Eq. (6). The error bars are purely statistical. In the $\pi^-$ case there are systematic uncertainties of 6% in the cross section and 9% in the analysing powers.

The results for the analysing power of the $\bar{p}n \rightarrow \{pp\}_s, \pi^-$ reaction are displayed in Fig. 4, with $A_y(d\sigma/d\Omega)$ being shown in panel a and $A_y$ in panel b. The agreement with the TRIUMF $A_y$ data [5] is reasonable at large angles and both show the strong and rather asymmetric oscillation in the central region. However, there are clear discrepancies for $\theta_\pi \lesssim 60^\circ$, as there are also for the cross section shown in Fig. 3.

Fitting the weighted $A_y$ distribution with the form of Eq. (2) requires at least the three terms given in Table 1. The associated curve is shown in Fig. 4a and this divided by the parameterisation of the cross section in panel b.

The spin structure of the $pn \rightarrow \{pp\}_s, \pi^-$ reaction is identical to that of $pp \rightarrow \{pp\}_s, \pi^0$, which was already presented in [3]. The cross section and analysing power can be written in terms of two scalar amplitudes $A$ and $B$ through

\[
\frac{d\sigma}{d\Omega} = \frac{k}{4p} \left[ |A|^2 + |B|^2 + 2 \Re[AB^\ast] \cos \theta_\pi \right],
\]

\[
A_y \left( \frac{d\sigma}{d\Omega} \right)_0 = \frac{k}{4p} \left( 2 \Im[AB^\ast] \sin \theta_\pi \right).
\]

(3)

Keeping terms up to pion $d$ waves, the $pp \rightarrow \{pp\}_s, \pi^0$ data at 353 MeV [3] can be parameterised in terms of the three amplitudes $M^p_1, M^p_3,$ and $M^p_5,$ corresponding to the transitions, $3P_0 \rightarrow 1S_0 s, 3P_2 \rightarrow 1S_0 d,$ and $3F_2 \rightarrow 1S_0 d,$
respectively. In proton-neutron collisions there are also the two $p$-wave transitions, $^3S_1 \rightarrow ^1S_0p$ and $^3D_1 \rightarrow ^1S_0p$ that arise in the isospin $I = 0$ case, and for these we introduce amplitudes $M_s^P$ and $M_s^D$, respectively.

In terms of these partial waves, $A$ and $B$ become

$$A = \frac{1}{\sqrt{2}} \left[ M_s^P - \frac{1}{2} M_d^P + M_d^F \right] \left( \cos \theta_p - \frac{1}{2} \right) + M_p^D \cos \theta_p \right],$$

$$B = \frac{1}{\sqrt{2}} \left[ M_s^P - \frac{3}{2} M_p^D + (M_d^P - \frac{2}{3} M_d^F) \cos \theta_p \right].$$

(4)

It is clear from the very different behaviour of the angular distributions in $\pi^0$ and $\pi^-$ production that the extra $p$-wave amplitudes in Eq. (4) must be very large and that it will not be justified to discard their interference with $M_s^P$.

Keeping terms up to $p$-$d$ interference but omitting the squares of the $d$-wave amplitudes, we find that

$$a_0 = \frac{1}{2} |M_s^P|^2 + \frac{1}{4} |M_p^D|^2 - \frac{1}{2} |M_d^F|^2 - \frac{1}{4} \Re \left[ M_s^P \left( M_d^P + \frac{3}{2} M_d^F \right) \right]$$

$$a_1 = \Re \left[ M_s^P \left( M_s^P + \frac{1}{2} M_p^D \right) + \frac{2}{3} M_s^P \left( M_p^P - \frac{2}{3} M_p^D \right) \right] - \frac{2}{3} M_d^F \left( M_d^F \right)$$

$$a_2 = \frac{1}{2} |M_p^D|^2 + \Re \left[ M_s^P \left( M_d^P + \frac{1}{2} M_d^F \right) + M_s^P \left( M_p^P - \frac{2}{3} M_d^F \right) \right]$$

(5)

By neglecting the small coupling between the $^3P_2$ and $^3F_2$ partial waves, and imposing the Watson theorem to determine the phases, it was possible to extract values for the complex amplitudes $M_s^P$, $M_p^D$, and $M_d^F$ from the analysis of the $pp \rightarrow \{pp\}_s \pi^0$ reaction [3]. Such an approach would not be valid for the $p$-wave terms because of the very strong coupling between the incident $^3S_1$ and $^3D_1$ waves. Nevertheless, although there is a significant overall relative uncertainty between the $\pi^-$ and $\pi^0$ production data, associated with luminosity and other systematic effects, it is clear from the comparison of the seven free parameters in Eq. (5) with the ten observables in Table 1 that the system is over determined. As a consequence, if an acceptable solution is achieved it would support the approximation made in our analysis, such as the neglect of higher partial waves, $d$-$d$ interference and the effect of coupling between the $^3P_2$ and $^3F_2$ partial waves.

The best fit to the combined $pp \rightarrow \{pp\}_s \pi^0$ and $pn \rightarrow \{pp\}_s \pi^-$ data sets is obtained with

$$M_s^P = (55.3 \pm 0.4) - (14.7 \pm 0.1)i \sqrt{\text{nb/sr}},$$

$$M_d^P = -(26.6 \pm 1.1) - (8.6 \pm 0.4)i \sqrt{\text{nb/sr}},$$

$$M_d^F = 5.3 \pm 2.3 \sqrt{\text{nb/sr}},$$

$$M_p^D = -(32.4 \pm 2.2) + (17.3 \pm 2.7)i \sqrt{\text{nb/sr}},$$

$$M_p^D = -(109.6 \pm 9.6) + (140.7 \pm 4.0)i \sqrt{\text{nb/sr}}.$$  (6)

Since this solution has $\chi^2$/NDF = 89/82, it shows that our truncated expansions can give a very good description of the data. The contribution from the $^3F_2 \rightarrow ^1S_0d$ transition is clearly very small and, if one eliminated $M_f^P$ completely, it would give only a marginally poorer fit with $\chi^2$/NDF = 94/82. Note, whereas the phases of $M_s^P$, $M_s^P$ and $M_d^F$ were imposed (see above), the phases of $M_s^P$ and $M_p^D$ were extracted from the data.

The quality of the fits can also be judged from the comparison of the curves in Figs. 3 and 4 with the data. The residual small discrepancies in the description of the analysing power might, of course, be due to the neglect of some of the smaller terms. However, it should also be borne in mind that the main systematic uncertainty, namely the relative normalisations between the $pp \rightarrow \{pp\}_s \pi^0$ and $pn \rightarrow \{pp\}_s \pi^-$ data sets, has not been included in the determination of the parameters. On the other hand, adjusting this by a few percent would not lead to any qualitative changes in the solution of Eq. (6).

Another way of judging the changes introduced by making a global fit to all the data simultaneously rather than fits to individual distributions is to look by how much the parameters themselves were changed by this procedure. These are shown in Table 1. No changes at all are to be noticed for the $pp \rightarrow \{pp\}_s \pi^0$ reaction and for the $pn \rightarrow \{pp\}_s \pi^-$ case it is only $a_{3}(pm)$ where the difference is greater than the error bars.

The conclusions that one can draw from Eq. (6) are first that, although $d$-wave pion production is significant, this is almost exclusively from the $^3P_2$ state since the $^3F_2 \rightarrow ^1S_0d$ transition is very weak. In the $pn \rightarrow \{pp\}_s \pi^-$ case the amplitudes are dominated by the $^3D_1 \rightarrow ^1S_0p$ transition.

A partial wave decomposition of the TRIUMF $\vec{p}n \rightarrow \{pp\}_s \pi^-$ data was attempted [5] but at the time there were no $\pi^0$ production results available to constrain the fit and the authors had to rely on the application of the Watson theorem even for the $^3S_1$ and $^3D_1$ waves, which are strongly coupled. Furthermore, their data did not extend over the whole angular domain and so it is not surprising that their partial wave results bear little relation to ours. They found negligible $d$-wave production and did not identify the dominant role played by the $^3D_1 \rightarrow ^1S_0p$ transition.

In summary, we have measured the differential cross section and proton analysing power of $\pi^-$ production in the quasi-free $\vec{p}n \rightarrow \{pp\}_s \pi^-$ reaction in the 353 MeV energy region over the whole angular domain. These complement the analogous data obtained on $\pi^0$ production in the $\vec{p}p \rightarrow \{pp\}_s \pi^0$ reaction. Through a careful use of the Watson theorem, an amplitude analysis of the combined data sets has been achieved and these have allowed the determination of the partial waves up to $\ell_\pi = 2$.

Some of the biggest uncertainties in the global amplitude analysis arise from the normalisations in the $pp \rightarrow \{pp\}_s \pi^0$ and $pn \rightarrow \{pp\}_s \pi^-$ data, which affect primarily the $s$- and $p$-wave production, respectively. The relative normalisation can be determined independently through a measurement of the transverse spin correlation parameter $A_{n,x}$ for the $pn \rightarrow \{pp\}_s \pi^-$ reaction [21]. Such data have already been taken and, when the results are available in 2012, these will
make the amplitude analysis more robust.

The pion-production amplitudes extracted must now be analysed using chiral perturbation theory and this will be an important step to provide a deeper understanding of low energy pion dynamics. If this programme is successful, it will provide further strong evidence that chiral perturbation theory can indeed be applied to $NN \rightarrow NN\pi$ provided that the large momentum transfers are taken into account properly. This is a precondition for the analysis of isospin-violating reactions in the same framework [22–24], which will shed light on the role of the quark mass term in low energy pion reactions.

We are grateful to other members of the ANKE Collaboration for their help with this experiment and to the COSY crew for providing such good working conditions, especially of the polarised beam. This work has been partially supported by the BMBF (grant ANKE COSY-JINR), RFBR (09-02-91332), DFG (436 RUS 113/965/0-1), the JCHP FFE, the SRNSF (09-1024-4-200), the Helmholtz Association (VH-VI-231), STFC (ST/F012047/1 and ST/J000159/1), and the EU Hadron Physics 2 project “Study of strongly interacting matter”

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