Vol. 29 (1998) ACTA PHYSICA POLONICA B No 11

NEAR-THRESHOLD PION PRODUCTION IN pN COLLISIONS AT CELSIUS*

J. Złomańczuk[a], R. Bilger[b], W. Brodowski[b], H. Calén[c]
H. Clement[b], J. Dyring[a], C. Ekström[c], G. Fäldt[a], K. Fransson[a]
L. Gustafsson[a], S. Häggström[a], B. Höistad[a], M. Jacewicz[a]
A. Johansson[a], J. Johansson[a], T. Johansson[a], A. Khoukaz[a]
K. Kilian[d], I. Koch[a], S. Kullander[a], A. Kupsc[e]
P. Marciniewski[e], B. Morosov[f], A. Mörtsell[a], W. Oelert[d]
R.J.M.Y. Ruber[a], U. Schuberth[a], B. Shwartz[g], J. Stepaniak[e]
A. Sukhanov[f], P. Sundberg[a], A. Turowiecki[h], G.J. Wagner[b]
Z. Wilhelmi[h], C. Wilkin[i], J. Zabierowski[j], and A. Zernov[f]

[a] Department of Radiation Sciences, Uppsala University
S-751 21 Uppsala, Sweden
[b] Physikalisches Institut, Tübingen University, D-72076 Tübingen, Germany
[c] The Svedberg Laboratory, S-751 21 Uppsala, Sweden
[d] IKP-Forschungszentrum Jülich GmbH, D-52425 Jülich, Germany
[e] Institute for Nuclear Studies, 00-681 Warsaw, Poland
[f] Joint Institute for Nuclear Research Dubna, 101000 Moscow, Russia
[g] Budker Institute of Nuclear Physics, Novosibirsk 630 090, Russia
[h] Institute of Experimental Physics, Warsaw University, 00-681 Warsaw, Poland
[i] Physics and Astronomy Dept., University College London
London WC1E 6BT, U.K.
[j] Institute for Nuclear Studies, 90-137 Łódź, Poland

(Received June 18, 1998)

The $pp \to pp\pi^0$ and $pn \to pp\pi^-$ reactions have been measured at 310, 320 and 340 MeV using the CELSIUS proton beam and ^{1}H and ^{2}H internal cluster-jet targets. The π^0 production at 310 MeV has been fully analyzed and a significant deviation from isotropy found in the pion angular distributions. This increases at small excitation energies of the final proton pair, suggesting that d-wave pion production is important even close to threshold. Evidence is also found for some P-wave excitation in the final p–p system.

PACS numbers: 13.60.Le, 13.75.Cs

* Presented at the Meson'98 and Conference on the Structure of Meson, Baryon and Nuclei, Cracow, Poland, May 26–June 2, 1998.

There are three independent total cross sections for single pion production in nucleon–nucleon collisions, denoted by σ_{if}, where the indices refer to the total isospin of the two nucleons in the initial and final states. The $pp \to pp\pi^0$ reaction corresponds to pure σ_{11}, whereas the production of final pn channels involve at least two amplitudes. Data on the three-body final state in $pp \to pn\pi^+$ are available [1] and complement the extensive data set on the two-body $pp \to d\pi^+$ reaction [2]. The $pn \to pp\pi^-$ reaction near threshold has recently been measured at RCNP [3] and TRIUMF [4] at small final pp excitation energies Q_{pp}. Using $\sigma_{01} = 2\sigma(pn \to pp\pi^-) - \sigma(pp \to pp\pi^0)$, this allows the extraction of a pure isospin cross section.

The measured $pp \to pp\pi^0$ cross sections near threshold [5, 6] seemed fairly isotropic but the recent RCNP experiment [3] shows that for $Q_{pp} <$ 3 MeV, there is a significant dependence upon the pion c.m. production angle θ_π, which increases steadily with beam energy. Since these results are dominated by the ${}^1S_0$ pp final state interaction (FSI), they imply that there must be strong pion d-wave production associated with one of the ${}^3F_2$, ${}^3P_2 \to {}^1S_0\, d$ transitions interfering with the s-wave ${}^3P_0 \to {}^1S_0\, s$, which is the only surviving term at threshold.

To provide better data on σ_{11} and σ_{01} near threshold, over a wider range of Q_{pp}, we have used the PROMICE-WASA apparatus [7] to measure the $pp \to pp\pi^0$ and $pn \to pp\pi^-$ reactions at beam energies of $T_p = 310$, 320 and 340 MeV.

The experiment was carried out with an electron-cooled proton beam of the CELSIUS storage ring at the The Svedberg Laboratory. Using ^{1}H and ^{2}H cluster gas jet targets, integrated luminosities ranging from ≈ 30 nb^{-1} to 340 nb^{-1} were achieved. The detector system is described in detail in Ref. [7]. Both protons from the $pp\pi^0$ final state are measured in the forward scintillator hodoscope and tracker (FD). Their loss, down the beam-pipe hole subtending an angle of $\pm 4°$, is the principal source of detection inefficiency. The large geometrical acceptance ($\approx 70\%$ at 310 MeV) is reduced by close to 20%, mainly through the interaction of protons in the scintillator. Protons from π^0 production stop in the hodoscope and their energies and angles are measured to the accuracy of 4.5% and 0.5° (r.m.s.) respectively. The hodoscope modules were carefully calibrated and this leads to an essentially background-free missing mass peak, with a FWHM of only 2.2 MeV/c^2 (Fig. 1). Events in the range 130 to 140 MeV/c^2 are taken to be π^0's and no use is made of the π^0 decay information.

The quasi-free $pn \to pp\pi^-$ reaction with a deuteron target can easily be recognised by selecting events with three final charged particles, two of which are identified as protons. Fig. 2 shows the pp missing mass distribution for such events. The narrow peak (FWHM=12.5 MeV) at the neutron mass results from $pd \to ppn$, where the neutron has interacted in the scintillator,

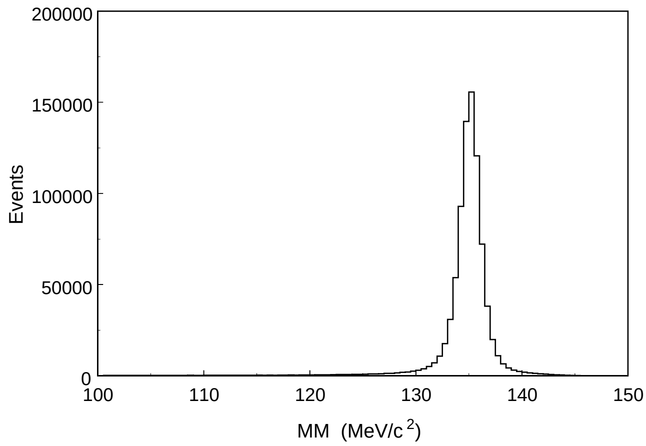

Fig. 1. Missing mass spectrum of the $pp \to ppX$ reaction at 310 MeV.

while the wider, clearly separated one, corresponds to pion production. The requirement of the missing mass to be in the area of the second peak defines the $pd \to ppp_s\pi^-$ reaction uniquely since no other channel with this topology can be produced at this energy. The protons are detected as before in the FD, but the third charged particle may also fall into the central detector (CD) consisting of two arrays of CsI modules and two plastic scintillator hodoscopes placed in front of them. The CD covers polar angles from 30° to 90° and azimuthal angles from -25° to 25°. For each $ppp_s\pi^-$ event, the pion

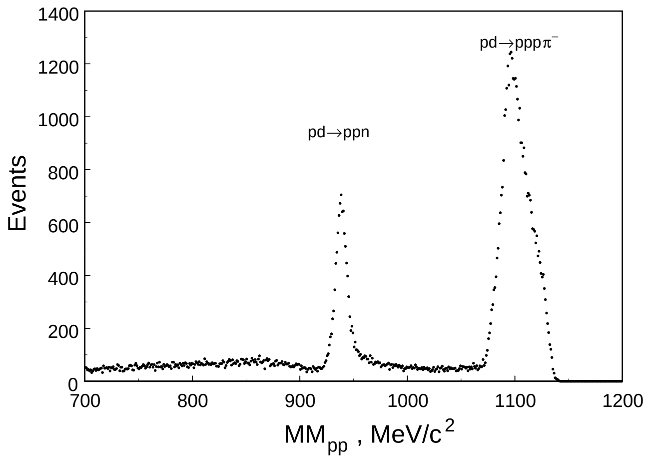

Fig. 2. Missing mass spectrum of the $pd \to ppX$ reaction at 320 MeV.

energy can be determined from the energy losses in the FD or CD modules, or calculated from kinematics using the measured momenta for the protons but only *angles* for the π^-. The second approach, used in this analysis, gives a much better resolution.

When using a deuteron as a neutron target, one has to assume that the proton in the deuteron acts as a spectator, *i.e.* it influences the interaction only through the associated Fermi motion of the bound neutron, and the matrix elements for π production off bound and unbound neutrons are the same.

The experimental distribution in the spectator energy is compared in Fig. 3 with the results of the phase space Monte Carlo (MC) simulation. The dotted curve has been obtained for the quasi-free $pn \to pp\pi^-$ reaction, with the π^- angular distribution being adjusted to match the data, while the dashed curve represents a model where both nucleons in the deuteron participate, both curves being normalized to the data. The experimental distribution is reproduced by the simulation and, for spectator energies below 10 MeV, the contribution from the quasi-free reaction is close to 85%, so the first assumption of the spectator model is well justified. It should be noted that the data show linear terms in $\cos\theta_\pi$ arising from interference between initial isospin-0 and 1 pn states.

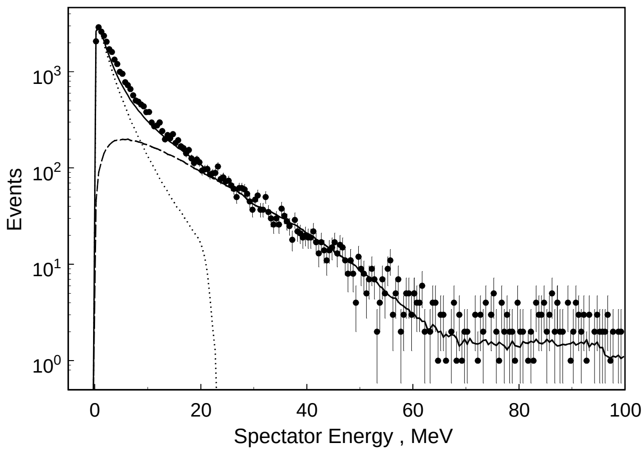

Fig. 3. Spectrum of the spectator (p_s) energy in the $pd \to pp\pi^- p_s$ reaction at 320 MeV.

At present only the $pp \to pp\pi^0$ reaction at 310 MeV has been fully analyzed [8]. Having almost 10^6 pions allowed us to study the π^0 angular distributions for different bins of Q_{pp}, and Fig. 4 shows that the cross sections are linear in $\cos^2\theta_\pi$. Both the angular distributions and the Q_{pp} spectrum shown in Fig. 5 are reproduced by the MC simulation if the matrix element squared is taken as

$$\begin{aligned}|M|^2 \;=\; & |A|^2 + 2\mathrm{Re}\,(A^*B)\frac{k^2}{\mu^2}\cos^2\theta_\pi + |B|^2\frac{k^4}{\mu^4}\,\cos^2\theta_\pi \\ & +|C|^2\frac{q^2}{\mu^2} + |D|^2\frac{k^2q^2}{\mu^4}\,\sin^2\theta_{pp}\,. \end{aligned} \tag{1}$$

Here μ is the pion mass, the momentum of the pion in the overall c.m. system is denoted by $\vec{k}$, $2\vec{q}$ is the relative momentum in the final two-proton system, and θ_{pp} is the angle between $\vec{q}$ and the beam direction. The amplitudes A, C, and D can be associated with transitions to Ss, Ps and Pp states respectively, whereas B corresponds to a mixture of Sd with Ss. It should be noted that in our experiment we cannot separate effects from the ${}^3F_2$ and ${}^3P_2$ initial waves.

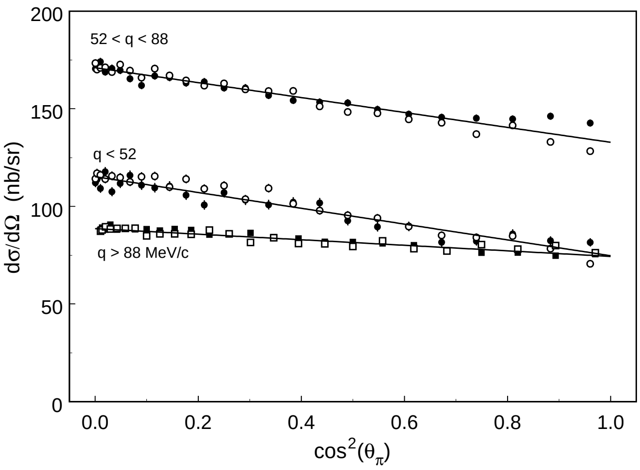

Fig. 4. Acceptance-corrected pion differential cross sections for $pp \to pp\pi^0$ in three bins of pp relative momentum. Due to the symmetry in the initial state, the data should be functions of $\cos^2\theta_\pi$ and the differences between the results in the forward and backward hemispheres, shown with open and closed symbols respectively, give a measure of the systematic uncertainties in our analysis.

The A and B amplitudes are subject to the same ${}^1S_0$ FSI. It is a common approximation to assume a universal enhancement factor $F_{\rm fsi}$ to be independent of the form of the pion-production operator, so that $|A|^2 = |A_0|^2\, F_{\rm fsi}(q)$, and similarly for B. We take the factor to be proportional to the square of the pp wave function at its peak ($r = 1$ fm), divided by the corresponding plane wave [8]. Apart from the explicit kinematic factors shown in Eq. (1), the amplitudes A_0, B_0, C and D are taken to be constant, with A_0 and B_0 being relatively real.

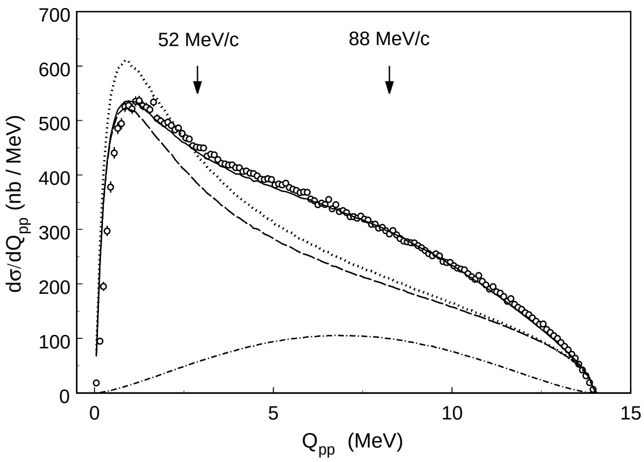

Fig. 5. Acceptance-corrected integrated $pp \to pp\pi^0$ cross section as a function of Q_{pp}. The dotted curve represents a purely S-wave calculation with FSI, and this is slightly decreased to the dashed curve through the introduction of the B term which contains some pionic s-wave as well as d-wave. Strength is clearly missing in the middle of the distribution and, in our parametrisation, this is provided by the Pp excitation shown with a dot-dashed line. The overall agreement of the full parametrisation (solid line) with the data is good except for the rise at small energies where the acceptance is small.

Taking $C = 0$ and $D = 1.05A_0$, corresponding to a $\approx 20\%$ Pp contribution in addition to the Ss, reproduces the momentum spectrum but not the angular distributions of the pion. Agreement is achieved here through the introduction of the Sd term with coefficient $B_0 = -(1.2 \pm 0.2)\,A_0$. The reduction in the integrated cross section due to the $Re(A^*B)$ term of Eq. (1) should be interpreted as being caused by the energy variation of the Ss term implicit in the parametrisation, rather than as an s–d interference effect.

Having fixed constant values of A_0, B_0, C and D from our experiment, we can compare our results with those of the RCNP group [3], who measured the same reaction for $Q_{pp} < 3$ MeV at four beam energies. The overall normalization and the variation of the slope with T_p are well reproduced up to the highest energy (Fig. 6).

The consistent picture deduced from our and the RCNP results [3] shows that even close to threshold the transitions to ${}^1S_0\,d$ state cannot be neglected in neutral pion production. This conclusion, which is based mainly upon the pion angular distribution, is fairly stable to the addition of other amplitudes or modifications of the FSI factor. Though our data are best reproduced with a 20% Pp excitation, such a contribution is harder to quantify because of the ambiguities in the amplitudes and the form of the FSI.

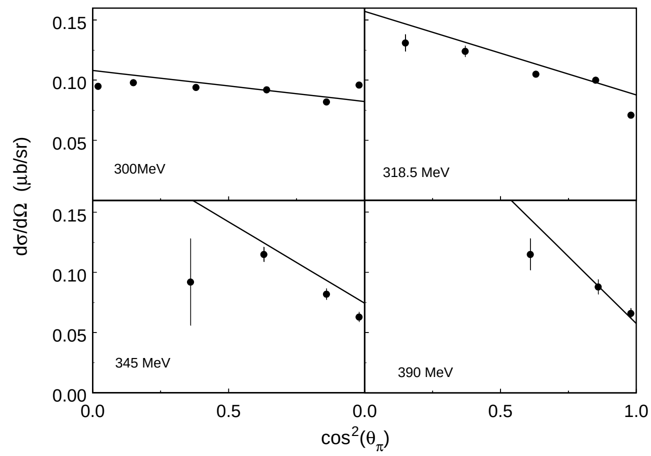

Fig. 6. Differential cross sections for $pp \to pp\pi^0$ at four different beam energies for events with $Q_{pp} < 3$ MeV. The RCNP data [3] are compared to the model used to fit our data with the same parameters, *viz* $B_0 = -1.2\,A_0$, $C = 0$ and $D = 1.05A_0$.

We are very grateful to the TSL/ISV personnel for their continued help during the course of this work. Discussions with K. Tamura about the importance of the pion angular distributions described in Ref. [3] were much appreciated. Financial support for this experiment and its analysis was provided by the Swedish Natural Science Research Council, the Swedish Royal Academy of Science, the Swedish Institute, the Polish Scientific Research Committee, the Russian Academy of Science, the German Bundesministerium für Bildung und Forschung [06TU886 and DAAD], and the European Science Exchange Programme.

REFERENCES

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

[2] R.A. Arndt, I.I. Strakovsky, R.L. Workman, *Phys. Rev.* **C50**, 2731 (1994), accessible from the SAID database http://clsaid.phys.vt.edu/~CAPS/said.

[3] Y. Maeda *et al.*, *πN Newsletter* **13**, 326 (1997); K. Tamura *et al.*, (submitted for publication).

[4] F.Duncan *et al.*, *Phys. Rev. Lett.* **80**, 4390 (1998).

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

[6] A. Bondar *et al.*, *Phys. Lett.* **B356**, 8 (1995); A. Mörtsell, PhD thesis (University of Uppsala), *Acta Universitatis Upsaliensis* **6**, 1997.

[7] H. Calén *et al.*, *Nucl. Instr. Meth.* **A379**, 57 (1996).

[8] J. Złomańczuk *et al.*, (submitted to *Phys. Lett.* **B**).