Production of the $^1S_0$ diproton in the $pp \rightarrow pp\pi^0$ reaction at 0.8 GeV

S. Dymov, M. Büscher, D. Gusev, M. Hartmann, V. Hejny, A. Kacharava, A. Khoukaz, V. Komarov, P. Kulessa, A. Kulikov, N. Lang, G. Macharashvili, T. Mersmann, S. Merziakov, S. Mikirtychiants, A. Mussgiller, D. Prasuhn, F. Rathmann, R. Schleichert, H. Ströher, Yu. Uzikov, C. Wilkin, S. Yaschenko

Abstract

The $pp \rightarrow pp\pi^0$ differential cross section has been measured with the ANKE spectrometer at COSY–Jülich for pion cms angles between 0° and 15.4° at a proton beam energy of 0.8 GeV. The selection of diproton pairs with an excitation energy $E_{pp} < 3$ MeV ensures that the final $pp$ system is dominantly in the spin-singlet $^1S_0$ state. The kinematics are therefore very similar to those of $pp \rightarrow d\pi^+$ but with different spin and isospin transitions. The cross sections are over two orders of magnitude smaller than those of $pp \rightarrow d\pi^+$ and show a forward dip that is even stronger than that seen at lower energies. The results should provide a crucial extra test of pion production models in nucleon–nucleon collisions.

© 2006 Elsevier B.V. All rights reserved.

PACS: 25.40.Ep; 25.40.Qa; 13.60.Le

Keywords: Nuclear reactions $^1\text{H}(p, pp)\pi^0$; $E = 0.8$ GeV; Measured $\sigma(E, \theta)$
should dominate while providing reasonable statistics. One important feature of the experimental data is that with the $E_{pp}$ selection the cross sections show a forward dip whereas, if no cut is applied on the excitation energy, then for the higher beam energies there is a forward maximum [9,10].

The threshold for $N\Delta$ production is well above 425 MeV and the data show no sign of being influenced in any clear way by the $\Delta$. We need to go to higher energies to investigate the effects of $P$-wave $\Delta N$ systems. As part of a programme to study the small $E_{pp}$ region in intermediate energy nuclear reactions, in particular in large momentum transfer deuteron breakup reactions [11,12], we have carried out a high statistics measurement of the $pp \rightarrow \{pp\}_s\pi^0$ reaction at $T_p = 800$ MeV for pion cm angles below 15.4°.

The experiment was performed at the magnetic spectrometer ANKE [13], placed at an internal target position of the COSY cooler synchrotron [14]. Fast charged particles, resulting from the interaction of the proton beam with the hydrogen cluster-jet target [15], were registered in the forward detector (FD) system [16]. Its hodoscope provided a trigger signal and an energy-loss measurement. It also allowed a determination of the differences in arrival times for particle pairs hitting different counter elements. The tracking system gave a momentum resolution $\sigma_p/p \approx 0.8$–1.2% for protons in the range (0.5–1.2) GeV/c.

The trigger used required the crossing of the two planes of the scintillation hodoscopes by at least one charged particle but, in the subsequent off-line analysis of the $pp \rightarrow \{pp\}_s\pi^0$ reaction, only events with two tracks in the FD were retained. In Fig. 1 is shown a two-dimensional scatter plot of the magnitudes of their two momenta corresponding to about half of our statistics. Due to the limited angular acceptance of ANKE, we observe kinematic correlations between the momenta of the registered particles for reactions with two and three particles in the final state. One therefore sees in the figure islands corresponding to $pp \rightarrow d\pi^+$ and bands resulting from $pp \rightarrow pn\pi^+$ and $pp \rightarrow pp\pi^0$. Candidates for the latter reaction are well separated from the other processes. Furthermore, in approximately 75% of cases the particles hit different counters in the hodoscope and the difference in their arrival time could also be used in the selection. The $d\pi^+$ pairs coming from the $pp \rightarrow d\pi^+$ reaction, which could potentially provide the most serious physical background, are separated from the $pp$ pairs from $pp \rightarrow pp\pi^0$ in time difference by more than at 8 ns, whereas the actual resolution is better than 0.5 ns.

The distributions of missing mass squared, $M^2_X$, are shown separately in Fig. 2 for single-counter and double-counter candidates with low excitation energy in the $pp$ system, $E_{pp} < 3$ MeV. In both cases one sees a very clean $\pi^0$ peak centred at 0.021 (GeV/c²)², which agrees with $n^2_{\pi^0}$ to well within our experimental precision. The widths of the Gaussian fits are compatible with those obtained from Monte Carlo simulations; the marginally narrower peak in the single-counter data is due to these events generally having a smaller opening angle resulting in the kinematics being slightly better defined. The backgrounds are small and slowly varying and two-pion production can be clearly excluded in either case. There is a small excess of events observed on the left side of the $\pi^0$ peak. These may correspond to single photon production through $pp \rightarrow \{pp\}_s\gamma$ and so the regions indicated by dashed lines in Fig. 2 have not been included in the Gaussian fits. Since this interpretation is not unambiguous and these events might still correspond to good $\pi^0$ events, we have added an extra 2% to the systematic error.

Given that the two data sets are completely compatible, they have been grouped together in the subsequent analysis. The resolution in excitation energy for the combined $pp \rightarrow pp\pi^0$ events was $\sigma (E_{pp}) \approx 0.2$–0.3 MeV for $E_{pp}$ in the range 0–3 MeV.

The value of the luminosity needed to determine the cross section was found by comparing the yield of $pp$ elastic scattering, measured simultaneously with the other reactions, with that deduced from the SAID data base [17]. The integrated lumi-
of a Monte Carlo simulation of the ANKE setup. This leads to resolution of the detectors and other known effects on the basis such a distribution by taking into account geometrical accept-

Values of the corresponding cross sections were obtained from spectra in the other intervals demonstrate a similar behaviour.

The rapid rise of the spectrum with $E_{pp}$, from threshold illustrated in Fig. 3(b) is typical of all intermediate energy reactions where one produces proton pairs and is induced by the $pp$ final state interaction. We have indeed observed exactly the same phenomenon in the $pd \rightarrow (pp)n$ reaction with the same apparatus at ANKE [11,12]. This effect is often parameterised, in the Migdal–Watson approximation [18], by the linear function $a(1 + b \sin^2 \theta_\pi^\mathrm{cm})$, where $a = (704 \pm 22 \mathrm{stat} \pm 32 \mathrm{syst}) \text{ nb/sr}$ and $b = 5.6 \pm 1.2$. With the same $E_{pp}$ cut as used here, a similar forward dip was observed in this reaction at lower energies, $T_p \leq 425 \text{ MeV} [8,9]$, though for these energies it was found not surprising that we find a larger slope parameter at 800 MeV.

The Migdal–Watson factor of Eq. (1) was used as an event generator together with phase space to provide candidates which were then traced through the experimental setup, taking into account all its known features. The resulting smoothed curve, shown in Fig. 3(a), provides a semi-quantitative description of the data which is quite sufficient for our purpose, where we quote cross sections summed over energy. The data are a little above the curves at the higher $E_{pp}$ and we cannot exclude some small $P$-wave contribution though globally the angular distribution of the $pp$ system in its rest frame shown in Fig. 4 is consistent with isotropy. It should be noted that the $^3P_0$ final state would also produce a flat distribution.

Due to the identity of the initial protons, the differential cross section is an even function of $\cos \theta_\pi^\mathrm{cm}$ and in Fig. 5 it is plotted versus $\cos^2 \theta_\pi^\mathrm{cm}$. The resolution in $\cos \theta_\pi^\mathrm{cm}$, which is always smaller than the bin size, varies from about 0.003 at $\theta_\pi^\mathrm{cm} = 15^\circ$ down to 0.001 at $0^\circ$. The cross section shows a monotonic decrease towards the forward direction and, as seen from the figure, this can be well parameterised by the linear function $a(1 + b \sin^2 \theta_\pi^\mathrm{cm})$, where $a = (704 \pm 22 \mathrm{stat} \pm 32 \mathrm{syst}) \text{ nb/sr}$ and $b = 5.6 \pm 1.2$. With the same $E_{pp}$ cut as used here, a similar forward dip was observed in this reaction at lower energies, $T_p \leq 425 \text{ MeV} [8,9]$, though for these energies it was found that $b$ was much smaller, being always less than 1.4. Since, for such small values of $E_{pp}$, the final diproton must be dominantly in an $S$-wave, constraints from spin–parity and Fermi statistics then require the pion to be in an even partial wave. As a consequence, the forward dip was attributed to an interference between the pion $s$- and $d$-waves [9]. Given that the influence of $d$-waves might be expected to increase with energy, it is perhaps not surprising that we find a larger slope parameter at 800 MeV.

Preliminary theoretical predictions have been made for the $pp \rightarrow (pp), \pi^0$ differential cross section at 800 MeV in a model that includes contributions from $P$-wave $\Delta N$ intermediate states [19,20]. The overall magnitude is similar to that which we have observed and, in particular, the forward slope, driven by the joint effects of the pion $s$- and $d$-waves, is well reproduced. In fact, if the theoretical curve were displaced by a mere
from Ref. [9]. The values of the production cross sections for spin-singlet production through the pion-exchange mechanism, where the large momentum transfer \(pd \rightarrow dp\) reaction is driven by a \(pp \rightarrow d\pi^+\) subprocess [25,26]. More quantitative estimates of the \(pp \rightarrow \{pp\}, \pi^0\) sub-process is used rather than the \(pp \rightarrow d\pi^+\), are currently under way [27].

It is intriguing to note that a very similar ratio to that of Table 1 has been observed for backward dinucleon production in the \(pd \rightarrow \{pp\}, n\) and \(pd \rightarrow dp\) reactions at intermediate energies [11]. Now such a connection would be natural within a one-pion-exchange mechanism, where the large momentum transfer \(pd \rightarrow dp\) reaction is driven by a \(pp \rightarrow d\pi^+\) subprocess [25,26]. More quantitative estimates of the \(pd \rightarrow \{pp\}, \pi^0\) cross section, where the \(pp \rightarrow \{pp\}, \pi^0\) sub-process is used rather than the \(pp \rightarrow d\pi^+\), are currently under way [27].

It is seen from Table 1 that there is a real lack of data on the \(pp \rightarrow \{pp\}, \pi^0\) reaction in the \(\Delta\) region and this could be usefully filled by further experiments at ANKE. It should also be noted that, unlike the complicated spin structure connected with the \(pp \rightarrow d\pi^+\) reaction, only two spin amplitudes which are functions of \(\cos^2 \theta\), are required to describe the \(pp \rightarrow \{pp\}, \pi^0\) reaction. These can be isolated, up to an unmeasurable overall phase, by determining the proton analysing power and the initial \(pp\) spin correlation \(C_{ss}\). Both of these experiments can be carried out at small angles using ANKE [28] and the resulting amplitude analysis will tie down even further \(\pi NN\) dynamics at intermediate energies.

### Acknowledgements

This work was supported in part by the BMBF grants ANKE COSY–1INR, Kaz-02/001 and Heisenberg–Landau programme. We are grateful to many other members of the ANKE Collaboration who provided strong support for the measurement. Important discussions with J.A. Niskanen and correspondence with I. Strakovsky are also gratefully acknowledged.

### References

[1] H. Garcilazo, T. Mizutani, \(\pi NN\) Systems, World Scientific, Singapore, 1990.
[2] H. Machner, J. Haidenbauer, J. Phys. G 25 (1999) R231.
[3] C. Hanhart, Phys. Rep. 397 (2004) 155.
[4] R.A. Arndt, et al., Phys. Rev. C 48 (1993) 1926.
[5] H.O. Meyer, et al., Nucl. Phys. A 539 (1992) 633.
[6] See for example: T.-S.H. Lee, D.O. Riska, Phys. Rev. Lett. 70 (1993) 2237.
[7] M.A. Moinester, et al., Phys. Rev. Lett. 52 (1984) 1203.
[8] T. Maeda, M. Matsuoka, K. Tamura, Nucl. Phys. A 684 (2001) 392c.
[9] Y. Bilger, et al., Nucl. Phys. A 693 (2001) 633.
[10] G. Rappenecker, et al., Nucl. Phys. A 590 (1995) 763.
[11] V. Komarov, et al., Phys. Lett. B 553 (2003) 179.
[12] S. Yaschenko, et al., Phys. Rev. Lett. 94 (2005) 072304.
[13] S. Barsov, et al., Nucl. Instrum. Methods A 462 (1997) 364.
[14] R. Maier, Nucl. Instrum. Methods A 390 (1997) 1.
[15] A. Khoukaz, et al., Eur. Phys. J. D 5 (1999) 275.
[16] S. Dymov, et al., Part. Nucl. Lett. 1 (2004) 40.
[17] SAID data base available from http://gwdac.phys.gwu.edu.
[18] K.M. Watson, Phys. Rev. 88 (1952) 1163;
A.B. Migdal, Sov. Phys. JETP 1 (1955) 2.
[19] J.A. Niskanen, Phys. Rev. C 43 (1991) 36.
[20] J.A. Niskanen, in preparation.
[21] M. Abdel-Bary, et al., Phys. Lett. B 610 (2005) 31.
[22] J. Hudomalj-Gabitzsch, et al., Phys. Rev. C 18 (1978) 2666.
[23] V. Abaev, et al., Phys. Lett. B 521 (2001) 158.
[24] Yu.N. Uzikov, C. Wilkin, Phys. Lett. B 511 (2001) 191.
[25] N.S. Craigie, C. Wilkin, Nucl. Phys. B 14 (1969) 477.
[26] V.M. Kolybasov, N.Ya. Smorodynskaya, Yad. Fiz. 17 (1973) 1211.
[27] Yu.N. Uzikov, C. Wilkin, in preparation.
[28] A. Kacharava, F. Rathmann, C. Wilkin, nucl-ex/0511028.