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Physics Letters B 661 (2008) 22–27
PHYSICS LETTERS B
www.elsevier.com/locate/physletb

Energy dependence of forward $^1S_0$ diproton production in the $pp \to pp\pi^0$ reaction

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Received 7 December 2007; received in revised form 29 January 2008; accepted 29 January 2008

Available online 1 February 2008

Editor: D.F. Geesaman

Abstract

The $pp \to \{pp\}_s\pi^0$ differential cross section has been measured with the ANKE spectrometer at COSY-Jülich for seven proton beam energies T_p between 0.51 and 1.97 GeV. By selecting proton pairs with an excitation energy of less than 3 MeV it is ensured that the final $\{pp\}_s$ system is in the $^1S_0$ state. In the measured region of $\theta_{pp}^{\text{cm}} \lesssim 18^\circ$, the data reveal a forward dip for $T_p \leqslant 1.4$ GeV whereas a forward peaking is seen at 1.97 GeV. The energy dependence of the forward cross section shows a broad peak in the 0.6–0.8 GeV region, probably associated with $\Delta(1232)$ excitation, and a minimum at 1.4 GeV. Some of these features are similar to those observed for the spin–isospin partner reaction, $pp \to d\pi^+$. However, the ratio of the forward differential cross sections of the two reactions shows a significant suppression of single pion production associated with a spin-singlet final nucleon pair.
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PACS: 25.40.Ep; 25.40.Qa; 13.60.Le

Keywords: Neutral pion production; Proton–proton collisions; Final state interactions

Single pion production in nucleon–nucleon collisions, $NN \to NN\pi$, is one of the principal tools used in the investigation of NN dynamics at intermediate energies [1–3]. Because of the large momentum transfers involved, even close to threshold, such a meson production process is sensitive to the short-distance part of the NN interaction.

The $pp \to d\pi^+$ reaction has been the subject of extensive experimental study with the measurement of many spin observables, as well as of the differential cross section from threshold up to several GeV. However, the information that this provides is restricted to final NN states with spin $S = 1$ and isospin $T = 0$. On the other hand, the $pp \to \{pp\}_s\pi^0$ process is kinematically very similar to this provided that the excitation energy in the final proton pair is very small. In this case, due to the Pauli principle, the protons must be in the singlet $^1S_0$ state, i.e., have quantum numbers $(J^P, T, L) = (0^+, 1, 0)$

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doi:10.1016/j.physletb.2008.01.051

compared to the $(1^+, 0, 0 \text{ and } 2)$ of the deuteron. Pion production in the two cases therefore involves different transition matrix elements so that a combined study of the two processes should yield greater insight into the reaction dynamics.

If we consider the $pp \to d\pi^+$ reaction as the limit of triplet $\{pn\}_t$ production in the $pp \to \{pn\}_t\pi^+$ channel, where the strong final state interaction produces the deuteron [4], the ratio of π^0 to π^+ cross sections will provide information on the relative strength of spin-singlet to spin-triplet production, i.e., give information on the relative probability of pion production at short distances in channels with different spin orientation of the final nucleons. Because of the smallness of the signal, attempts to identify spin-singlet production directly from data on the $pp \to pn\pi^+$ cross section have only yielded upper limits [5–7].

A small value of the singlet–triplet ratio is expected near threshold since s-wave isovector pion rescattering is absent for $pp \to pp\pi^0$ and heavy (ω) meson exchange provides the largest driving term [8]. A small value of the ratio is also predicted for energies around 0.4–0.6 GeV since the S-wave $\Delta(1232)N$ intermediate state that dominates the $pp \to d\pi^+$ cross section is forbidden by conservation laws in the $pp \to \{pp\}_s\pi^0$ case. The theoretical situation at higher energies is largely open. The position is rather similar on the experimental side since, away from the low energy domain, the only other published data in the $^1S_0$ conditions were limited to energies $T_p \leqslant 0.425$ GeV [9].

We have previously reported a measurement of the $pp \to \{pp\}_s\pi^0$ differential cross section obtained using the ANKE spectrometer [10] for the single beam energy of 0.8 GeV [11]. Here the two protons were detected at small angles with respect to the incident beam and cuts were made such that the excitation energy E_{pp} in the final pp system was less than 3 MeV. Under these conditions we expect the final $\{pp\}_s$ pair to be almost purely in the singlet $^1S_0$ state. It was found for this beam energy that the angular variation was rather strong but that at all the measured angles the cross section was orders of magnitude smaller than that for $pp \to d\pi^+$. To study the energy dependence of these effects, we present here further measurements taken over a wide range of energies, 0.508, 0.625, 0.700, 1.100, 1.400, and 1.970 GeV.

The magnetic spectrometer ANKE is placed at an internal beam station of the COSY cooler synchrotron of the Forschungszentrum Jülich. Fast charged particles, resulting from the interaction of the proton beam with the hydrogen cluster-jet target [12] and passing through the analysing magnetic field, were recorded in the forward detector (FD) system [13]. The FD system includes multiwire proportional chambers for tracking and a scintillation counter hodoscope for energy loss and timing measurements. The triggers employed required the crossing of the two planes of the hodoscope by at least one charged particle (SP-trigger) or by two particles (DP-trigger) [14]. When the DP-trigger was used for data taking, the SP-trigger ran (prescaled) in parallel for luminosity measurement and calibration purposes. The tracking system provided momentum resolution $\sigma_p/p \approx 1\%$ in the range of interest and resolution in the excitation energy of $\sigma(E_{pp}) \approx 0.2$–$0.8$ MeV for events with $E_{pp} < 3$ MeV.

Additional details of the experimental setup and the measurement procedure are to be found in Refs. [11,13,15,16]. The data at 0.8 GeV and above were taken during a single beam-time run, whereas the lower energy results were obtained from other ANKE calibration runs.

From measurements of the momenta of two charged particles in ANKE, the $pp \to pp\pi^0$ channel was isolated by determining the missing mass M_x in the reaction. In more than 80% of cases where two fast particles were detected, the tracks passed through different counters of the forward hodoscope. For these events the particles could be clearly identified as protons on the basis of the timing information. The difference of the arrival times of the two particles measured by the counters was compared with the time-of-flight difference deduced from the measured momenta, assuming that the particles both had the mass of the proton. For the remaining $\approx 20\%$ of events, the hypothesis was made that the two particles were indeed protons. As already shown for the 0.8 GeV data [11], the missing-mass distributions for both classes of events are very similar with only a slightly enhanced background when no timing information was available. The two sets were therefore combined in the subsequent analysis.

Fig. 1 presents examples of the measured missing-mass distributions in the π^0 region for events with $E_{pp} < 3$ MeV. In addition to the π^0 peak, a rise of counts is seen on the right-hand side due to two-pion production which seems to be largest at 1.1 and 1.4 GeV. This background gives little contribution in the π^0 region and the data were fitted as a sum of a Gaussian and straight line. The region close to $M_x^2 = 0$ was excluded from the fit since, as discussed for the 0.8 GeV data [11], there is the possibility here of some contribution from the $pp \to \{pp\}_s\gamma$ reaction. In all cases the peak position was consistent with m_{π^0} to within the experimental uncertainties of about ± 10 MeV$/c^2$. Events within $\pm 2\sigma$ of the central value were retained for the determination of the $pp \to pp\pi^0$ differential cross section. The numbers of π^0 events deduced in this way are given for the different energies in Table 1.

The luminosities recorded in Table 1 were obtained by measuring in parallel elastic proton–proton scattering using the SP trigger. The ANKE setup detects the fast proton produced by this reaction for cms angles between about 10° and 30°. However, to avoid regions where the acceptance changes rapidly with angle, only data from the range $15° < \theta_p^{\text{cm}} < 24°$ were retained for 1.4 GeV and below while at 1.97 GeV the interval $17° < \theta_p^{\text{cm}} < 27°$ was selected. After corrections for acceptance, the numbers of events in several bins of θ_p^{cm} were compared with the values of the elastic differential cross section taken from the SP07 solution provided by the SAID phase shift analysis [17]. The precision of these predictions was checked by looking at experimental data at small angles from which it was assessed to be typically about $\pm 4\%$, though a little larger at 2 GeV.

A full Monte Carlo simulation of the ANKE spectrometer has been developed within the framework of the GEANT program [18]. This allowed us to estimate the acceptance factors

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