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On the Production of $\pi^+\pi^+$ Pairs in pp Collisions at 0.8 GeV

S. Abd El-Samad[8], R. Bilger[6], K.-Th. Brinkmann[2,10], H. Clement[6], M. Dietrich[6], E. Doroshkevich[6], S. Dshemuchadse[5,2], K. Ehrhardt[6], A. Erhardt[6], W. Eyrich[3], A. Filippi[7], H. Freiesleben[2], M. Fritsch[1], R. Geyer[4], A. Gillitzer[4], J. Hauffe[3], D. Hesselbarth[4], R. Jaekel[2], B. Jakob[2], L. Karsch[2], K. Kilian[4], J. Kress[6], E. Kuhlmann[2], S. Marcello[7], S. Marwinski[4], R. Meier[6], K. Möller[5], H.P. Morsch[4,9], L. Naumann[5], J. Ritman[4], E. Roderburg[4], P. Schönmeier[2,3], M. Schulte-Wissermann[2], W. Schroeder[3], F. Stinzing[3], G.Y. Sun[2], J. Wächter[3], G.J. Wagner[6], M. Wagner[3], U. Weidlich[6], A. Wilms[1], S. Wirth[3], G. Zhang[6a], and P. Zupranski[9]

[1] Ruhr-Universität Bochum, Germany
[2] Technische Universität Dresden, Germany
[3] Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany
[4] Forschungszentrum Jülich, Germany
[5] Forschungszentrum Rossendorf, Germany
[6] Physikalisches Institut der Universität Tübingen, Germany
[7] University of Torino and INFN, Sezione di Torino, Italy
[8] Atomic Energy Authority NRC Cairo, Egypt
[9] Soltan Institute for Nuclear Studies, Warsaw, Poland
[10] Rheinische Friedrich-Wilhelms-Universität Bonn
(COSY-TOF Collaboration)

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Abstract. Data accumulated recently for the exclusive measurement of the $pp \to pp\pi^+\pi^-$ reaction at a beam energy of 0.793 GeV using the COSY-TOF spectrometer have been analyzed with respect to possible events from the $pp \to nn\pi^+\pi^+$ reaction channel. The latter is expected to be the only $\pi\pi$ production channel, which contains no major contributions from resonance excitation close to threshold and hence should be a good testing ground for chiral dynamics in the $\pi\pi$ production process. No single event has been found, which meets all conditions for being a candidate for the $pp \to nn\pi^+\pi^+$ reaction. This gives an upper limit for the cross section of 0.16 μb (90% C.L.), which is more than an order of magnitude smaller than the cross sections of the other two-pion production channels at the same incident energy.

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1 Introduction

The two-pion production in nucleon-nucleon collisions connects $\pi\pi$ dynamics with baryon and baryon-baryon degrees of freedom. As predicted by the pioneering work of the Valencia group [2] the two-pion production process in general is governed by excitation and decay of baryon resonances. In systematic studies of two-pion production channels by exclusive measurements of solid statistics at CELSIUS [3,4,5,6,7] and COSY [8] it has been demonstrated that the excitation of the Roper resonance and its subsequent two-pion decay is the leading process near threshold in $pp \to pp\pi^+\pi^-$ and $pp \to pp\pi^0\pi^0$ channels. At higher energies $T_p > 1$ GeV the $\Delta\Delta$ process takes over the leading role . In addition, the isospin decomposition of the data available in all four pp initiated $\pi\pi$ channels $pp\pi^0\pi^0$, $pp\pi^+\pi^-$, $pn\pi^+\pi^0$ and $nn\pi^+\pi^+$ gives evidence for the active role of another, higher-lying Δ resonance, most likely the $\Delta(1600)$ [7]. The latter appears to be most dominant in the $nn\pi^+\pi^+$ channel at energies $T_p > 1$ GeV. At energies close to threshold the resonance contributions are expected [2] to vanish in this channel. Hence, its near-threshold cross section is predicted to be very small, however, most sensitive to non-resonant chiral terms [2]. This situation therefore provides a unique chance to test chiral dynamics in the two-pion production process on experimental data. The data base for the $nn\pi^+\pi^+$ channel is very sparse with just a few low-statistics bubble-chamber results [9,10,11] and one exclusive measurement at CELSIUS-WASA [7]. All these data are taken in the resonance region at energies $T_p > 1$ GeV, where the cross section in this channel is already sizable. At low energies, which are of interest here, no data exist so far for this channel.

[a] present address: Peking University

Correspondence to: H. Clement
email: clement@pit.physik.uni-tuebingen.de

2 Experiment

2.1 Detector setup

Since the experimental setup was discussed in detail already in Refs. [8,12,13], we give here only a short account. The measurements were carried out at the Jülich Cooler Synchrotron COSY using the time-of-flight spectrometer TOF at one of its external beam lines. The TOF spectrometer was used in its short version, in order to minimze the decay of pions before their arrival in the stop detectors and to maximize the solid angle covered by the stop detectors system consisting of Quirl with Central Calorimeter and the Ring detector system. At the entrance to the detector system the beam – collimated to a diameter smaller than 2 mm – hits the thin-walled LH_2 target. At a distance of 22 mm downstream of the target the two layers of the start detector were placed followed by a two-plane fiber hodoscope and finally the TOF-stop detector system at a distance of 1081 mm downstream the target. The stop detector system consists in its central part of the so-called Quirl, a 3-layer scintillator system followed by the Central Calorimeter and in its peripheral part of the so-called Ring, also a 3-layer scintillator system built in a design analogously to the Quirl, however, with inner and outer radii of 560 and 1540 mm, respectively. The Quirl-Calorimeter system serves for the identification of charged particles and of neutrons as well as for measuring the energy of charged particles. The calorimeter consists of 84 hexagon-shaped scintillator blocks of length 450 mm, which suffices to stop deuterons, protons and pions of energies up to 400, 300 and 160 MeV, respectively. The energy calibration of the calorimeter was performed by detecting cosmic muons. The total polar angle coverage was $3^\circ \leq \Theta^{lab} \leq 49^\circ$ with the central calorimeter covering the region $3^\circ \leq \Theta^{lab} \leq 28^\circ$.

2.2 Particle identification and event reconstruction

In the experiment the trigger suitable for the search for $nn\pi^+\pi^+$ events required two hits in the Quirl and/or Ring associated with two hits in the start detector. Tracks of charged particles are reconstructed from straight-line fits to the hit detector elements in start, fiber and stop detectors. They are accepted as good tracks, if they originate in the target and have a hit in each detector element the track passes through. In this way the angular resolution for charged tracks is better than 1° both in azimuthal and in polar angles. If there is an isolated hit in the calorimeter with no associated hits in the preceding detector elements, this hit qualifies as a neutron candidate. In this case the angular resolution of the neutron track is given by the size of the hit calorimeter block. i.e. by 7 - 8°. For charged particles the energy resolution of the calorimeter is about 4%. It is superior to that from time-of-flight measurements due to the short path length. However, for the Quirl and Ring elements the time-of-flight resolution is much better than the ΔE resolution. Hence, for particle identification in the Quirl-Calorimeter system we used the Quirl time-of-flight information together with the particle energy deposited in the calorimeter [8,12,13]. In addition there is the delayed pulse technique [8] installed, which can be used to positively identify π^+ particles.

For the Ring system there is no particular particle identification. However, the maximum possible laboratory polar angle for nucleons emerging from two-pion production events is $\approx 30^\circ$. Therefore practically all these nucleons are confined to the angular range of the Quirl-Calorimeter system and identified there. Also due to their large velocity the pions emerging from two-pion production are separable to a large extent in the Ring from protons emerging from single-pion production.

The $nn\pi^+\pi^+$ channel is selected by identifying two neutrons and two pions in the Calorimeter or alternatively only one pion in the Calorimeter, when the second charged track is in the Ring. The thus selected candidate events have then finally been subjected to a kinematical fit. Since all four-vectors of the ejectiles with the exception of the neutron kinetic energies have been determined experimentally, these fits have two overconstraints.

The absolute cross section is obtained by relative normalization to the data for the $pp\pi^+\pi^-$ channel, which have been obtained simultaneously in the experiment. Since the phase space distributions for both reactions are essentially identical, the only major difference lies in the efficiency of proton versus neutron detection. The latter has been determined as $\approx 36\%$ by measurement of the $pp \to pn\pi^+$ reaction [13].

3 Results

The final analysis of candidates for $nn\pi^+\pi^+$ events has been performed in two ways. In the first most stringent way we required that the two π^+ candidates of an event not only are identified by the time-of-flight versus deposited-energy information, but also by the delayed pulse technique requiring hits in the Calorimeter. As a result no single event passed the required conditions.

Since the identification by the delayed pulse technique has an efficiency of only 25% [8], if all four particles of the event hit the Calorimeter, we have abstained from requiring it furthermore. We can do so, since the selected events are composed of exactly four tracks with two of them being identified as neutral and two as charged. By charge conservation the two detected charged tracks must then be of positive charge.

With this relaxed condition, which increases the efficiency for the detection of $nn\pi^+\pi^+$ events by more than an order of magnitude since we also can use now the events with one pion hit in the Ring detector, we reanalyzed all possible events. Again we find no single candidate, which meets all imposed conditions for being recognized as a $nn\pi^+\pi^+$ event. This finding corresponds to an upper limit for the total cross section of 0.16 μb (90% C.L.), which is more than an order of magnitude smaller than that of the other two-pion production channels $pp\pi^+\pi^-$, $pp\pi^0\pi^0$ and $np\pi^+\pi^0$ at $T_p = 0.8$ GeV.

In Fig.1 we show the energy dependence of the total cross section of the $pp \to nn\pi^+\pi^+$ reaction. Plotted are all available data [9,10,11,7] including the result of this work. They are compared to the theoretical calculations of Ref. [2] as well as to the the cross section assumed for the isospin decomposition of the two-pion production process [7] (shaded band). The result of this work is compatible with the extrapolation towards lower energies assumed in the isospin decomposition work. It is presumably also in good agreement with the Valencia model calculations. Unfortunately these calculations stop at a cross section of 1 μb in Ref. [2]. It should be noted that these calculations fall low at high energies, since they do not include the $\Delta(1600)$ excitation as pointed out in Ref. [7]. From the energy dependence shown in Fig. 1 for the $\Delta\Delta$ process, which is qualitatively also followed by that of the $\Delta(1600)$ process, we see that these resonance contributions die out at low energies. The same is true for the process called σ^{semi} in Fig. 1, which denotes the Roper excitation with subsequent single-pion decay and associated with a simultaneous non-resonant production of a second pion, graphs (6) - (7) in Ref. [2]. The nonresonant contribution denoted in Fig. 1 by σ^{nonres} and corresponding to the so called chiral terms given by the graphs (1) - (3) in Ref. [2] exhibits a substantially smaller (phase space like) energy dependence and hence is expected to be the dominant term in the near-threshold region.

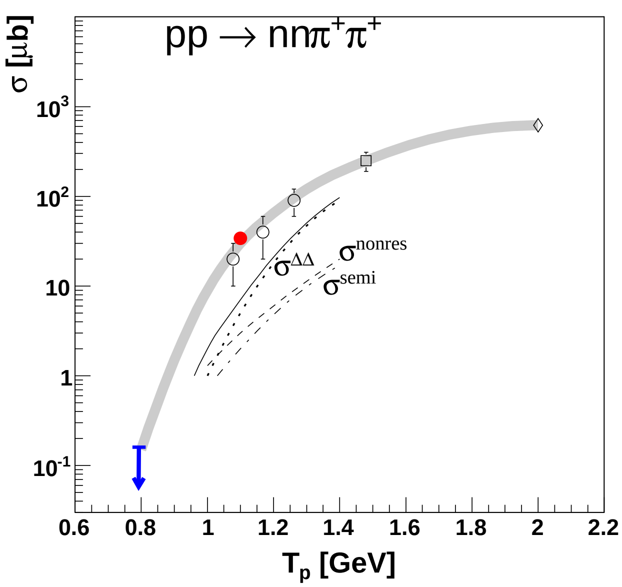

Fig. 1. (color online) Energy dependence of the total cross section for the $pp \to nn\pi^+\pi^+$ reaction. The thick vertical arrow represents the experimental result of this work. Open symbols denote the previous measurements [9,10,11] and the solid circle the recent result from an exclusive measurement at CELSIUS/WASA [7]. The curves drawn show the predictions of Ref. [2]. For non- and semi-resonant contributions they are given by the dashed (σ^{nonres}: contributions from diagrams (1) - (3) in Ref. [2]) and dash-dotted (σ^{semi}: contributions from diagrams (6) - (7) in Ref. [2]) lines. The dotted line denotes the $\Delta\Delta$ excitation process and the solid line the full calculation. The shaded band exhibits the cross section assumed for the isospin decomposition [7].

4 Summary

We have presented the first measurement of the $pp \to nn\pi^+\pi^+$ reaction at $T_p \approx 0.8$ GeV. Though no single event has been found, which meets all conditions for belonging to the $pp \to nn\pi^+\pi^+$ reaction process, it provides an upper limit for the total cross section of 0.16 μb (90% C.L.). This confirms the theoretical prediction that the cross section is unusually small compared to the other two-pion production channels, since resonance contributions are supposed to vanish close to threshold in this channel. In consequence, this situation gives a unique access to nonresonant chiral terms contributing to the two-pion production process.

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