Exclusive Measurement of the $pp \to pp\pi^+\pi^-$ Reaction Near Threshold

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The $pp \to pp\pi^+\pi^-$ reaction has been measured exclusively near threshold at CELSIUS. The total cross sections are nearly an order of magnitude lower than expected from previous inclusive measurements. The differential cross sections reveal $pp \to pp^*(1440) \to pp\sigma = pp(\pi^+\pi^-)_{I=\ell=0}$ as the dominant process as well as significant contributions from $p^* \to \Delta^{++}\pi^- \to p\sigma$. The observed anisotropy in the proton angular dependence is consistent with heavy-meson exchange. In the invariant mass spectra, no narrow structures of statistical relevance (3σ) are found.

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The double pion production in nucleon-nucleon (NN) collisions offers a variety of aspects concerning the dynamics of the total system as well as that of its subsystems $\pi\pi$, NN, πN, $\pi\pi N$, and πNN. Apart from small nonresonant chiral contributions, the double pion production process is expected to be dominated by excitation of one or both participating nucleons [1]. Since single $\Delta(1232)P_{33}$ excitation leads to the emission of only a single pion, the excitation of $N^*(1440)P_{11}$ in one of the participating nucleons with subsequent two-pion decay has the potential to dominate at low energies. This offers the possibility to study the Roper resonance $N^*(1440)$ and its decay branches, which is particularly interesting if the reaction proceeds via $pp \to pp^* \to pp\sigma := pp(\pi^+\pi^-)_{I=\ell=0}$, i.e., the direct decay into the σ channel, since this branch is hard to access in other reactions. Whereas the Δ and also higher-lying resonances are quite well understood in their basic quark structure, this is not the case for $N^*(1440)$, the second excited state of the nucleon. Recent calculations [2] even describe the Roper resonance by meson-nucleon dynamics alone, whereas another recent investigation [3] proposes it to be actually two resonances with one of them being the breathing mode monopole excitation of the nucleon. In all these aspects, the decay $N^* \to N\sigma$ plays an important role. Another important issue in this context is whether σ itself is a meson of basic $q\bar{q}$ structure or possibly also just of dynamical origin. Since we deal here with the $\pi\pi$ production close to threshold, this issue is not of decisive relevance here, and we will use the notation σ just as an abbreviation for the system $(\pi^+\pi^-)_{I=l=0}$.

All previous data on this reaction below $T_p = 900$ MeV stem from inclusive magnetic spectrometer measurements [4,5] or low-statistics bubble chamber experiments [6–8], which partly have also been inclusive [7,8]. We have carried out high-statistics exclusive measurements of the $pp \to pp\pi^+\pi^-$ reaction at the CELSIUS storage ring at $T_p = 650$, 680, 725, and 750 MeV using the PROMICE/WASA detector setup with a cluster jet H_2 target [9]. Protons and pions have been registered in the forward detector, which covers the polar angle range $4° \leq \Theta \leq 21°$. Protons have been identified by the $\Delta E - E$ method, positive pions in addition by their delayed pulse from subsequent muon decay. The identified $pp\pi^+$ events yield a narrow π^- peak (9 MeV FWHM) essentially free of background in the $pp\pi^+$ missing mass spectrum [10,11]. From the measured four momenta of p, p, and π^+, the full $pp\pi^+\pi^-$ events have been reconstructed by kinematical fits with one overconstraint. Detector acceptance and efficiencies have been deduced from Monte Carlo (MC) simulations of the detector setup. The efficiencies are smooth over the whole range of observables shown in Figs. 2 and 3 (below) and have been checked against single pion production data taken simultaneously as well as separately. The absolute normalization of the data has been obtained from monitoring the absolute luminosity of the experiment by the simultaneous measurement of elastic scattering and its comparison to literature data

[12]. The two protons of each $pp\pi^+\pi^-$ event have been treated on equal footing. Hence, for constructing the subsets $p\pi^+$, $p\pi^-$, and $p\pi^+\pi^-$, always both protons have been taken into account, thereby averaging over both possibilities.

In this Letter, we concentrate on measurements at $T_p = 750$ MeV [10], where most of the statistics has been accumulated. The 725 MeV data give very similar differential distributions, however, are of much less statistics. The measurements at 650 and 680 MeV, as well as those for other two-pion-production channels, are presented in a separate paper [13]. For incident energies $T_p = 650-750$ MeV, i.e., 22–64 MeV above threshold in the overall center-of-mass system (c.m.s.), the detector covers about 30% of the full phase space of $NN \to NN\pi\pi$. The data have been efficiency corrected and extrapolated [10,13] to 4π with the help of MC simulations for the reaction and for the detector response. By use of different models (see below) in the MC simulations, we estimate systematic errors of these corrections to be below 5%. The obtained integral cross sections in the overlap region are approximately an order of magnitude below previous bubble chamber data [7], however, in tentative accordance with the LAMPF datum [4] at $T_p = 800$ MeV (Fig. 1). We stress that the cross sections for single meson production measured during the beamtime periods for $\pi\pi$ production or measured in dedicated runs agree very well (see, e.g., [14–16]) with the world database on these reactions.

Figures 2 and 3 show sample differential cross sections. All distributions are smooth within statistics. The invariant mass spectra $M_{pp\pi^+}$ and $M_{pp\pi^-}$ show no excursions of statistical significance, which could be interpreted as a signal of a narrow dibaryon resonance in these systems. In a previous test run [11] a spike was observed in $M_{pp\pi^-}$ at 2.063 GeV/c^2 with a statistical significance of $2-3\sigma$ (depending on the treatment of background). Part of this spike could be explained meanwhile by an inadequate detector response, which has been fixed by now [10]. On the 3σ level the new data, which comprise an order of magnitude better statistics, provide no evidence for narrow πNN resonances and give an upper limit of about 20 nb for their production cross section in this reaction. This limit is 2 orders of magnitude below the previous prediction [17].

Before discussing in detail the features emerging from the measurement of the differential cross sections, we shortly review the possible reaction mechanisms of the $\pi^+\pi^-$ production process. Hereby, we take advantage of the very comprehensive and detailed theoretical

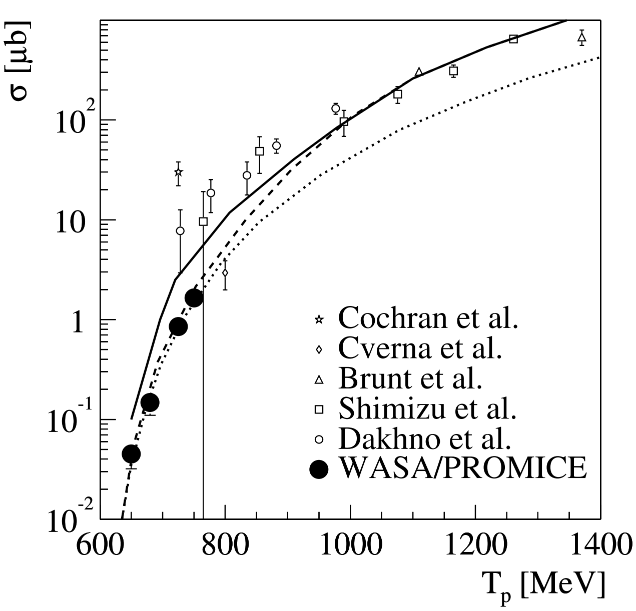

FIG. 1. Energy dependence of the total cross section. Results from this work are shown by solid dots; open symbols denote Refs. [4] (asterisks), [5] (diamonds), [8] (triangles), [6] (squares), and [7] (circles). The dotted line shows the pure phase space behavior normalized arbitrarily; solid and dashed lines represent theoretical predictions [1] with and without pp FSI, respectively.

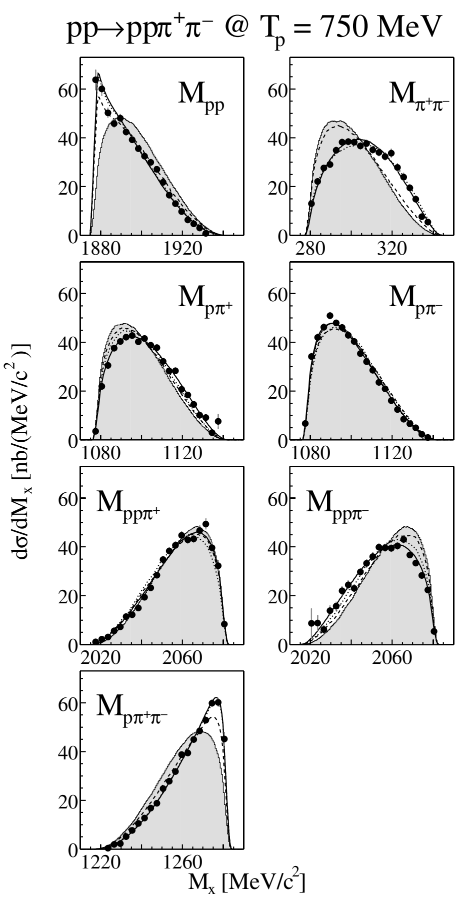

FIG. 2. Differential cross sections for invariant mass distributions M_{pp}, M_{π^+,π^-}, $M_{p\pi^+}$, $M_{p\pi^-}$, $M_{pp\pi^+}$, $M_{pp\pi^-}$, and $M_{p\pi^+,\pi^-}$. Solid dots show the experimental results. Shaded histograms and dashed lines represent MC simulations assuming pure phase space and phase space including pp FSI and σ exchange, respectively. The dotted lines and solid lines denote MC simulations for the coherent superposition of $pp \to pp^* \to pp\sigma \to pp(\pi^+\pi^-)_{I=l=0}$ and $pp \to pp^* \to p\Delta\pi \to pp(\pi^+\pi^-)_{I=l=0}$ employing Eqs. (2) and (3), respectively.

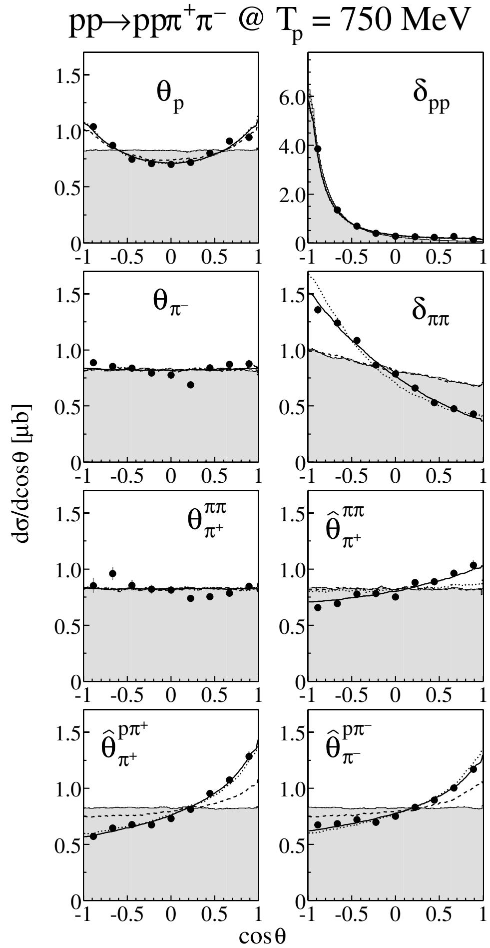

FIG. 3. Same as Fig. 2, but for the angular dependence on Θ_p, δ_{pp}, Θ_{π^-}, and $\delta_{\pi\pi}$ in the overall c.m. system and $\Theta_{\pi^+}^{\pi\pi}, \hat{\Theta}_{\pi^+}^{\pi\pi}$ in the $\pi\pi$ c.m. system, as well as $\hat{\Theta}_{\pi^+}^{p\pi^+}$ and $\hat{\Theta}_{\pi^-}^{p\pi^-}$ in the $p\pi$ c.m. systems.

investigation of Alvarez-Ruso *et al.* [1], in particular also from the analytic expressions given in the appendix therein. Apart from small [1] nonresonant contributions, there are in principle three resonant processes expected to contribute at energies $T_p \leq 1$ GeV: $pp \to pp^* \to pp\sigma, pp \to pp^* \to p\Delta\pi$, and $pp \to \Delta\Delta$. The direct decay of the Roper resonance into the σ channel is pure s-wave decay and governed by constants. Hence, the transition matrix element does not vanish at threshold. Since the other processes are strongly momentum dependent, the process $pp \to pp^* \to pp\sigma$ should dominate near threshold. Also, since for this route all particles originating from the p^* decay are in relative s wave, the angular distributions of the emitted particles are expected to be isotropic with the possible exception of the proton angular distribution. In case of s-wave meson production, the latter is just governed by the meson exchange between the colliding protons. For σ exchange, e.g., we then get the transition amplitude:

$$\mathcal{A}_\sigma \sim (\bar{u}_3 u_1) \frac{1}{q^2 - m_\sigma^2} (\bar{u}_4 u_2), \qquad (1)$$

where u_i are the bispinors for the incoming ($i = 1,2$) and the outgoing ($i = 3,4$) nucleons, and q is the four-momentum transfer. Antisymmetrization and evaluation of this amplitude yields then $\sigma(\Theta_p) \sim 1 - a\cos^2(\Theta_p)$ to leading order, with the coefficient $a > 0$ depending on proton momenta and the mass of the exchange particle. Here, Θ_p denotes the proton c.m.s. angle. For ρ exchange also $a > 0$ is obtained, whereas π exchange leads to $a < 0$ due to its pseudoscalar character.

The process $pp \to pp^* \to p\Delta\pi$ depends on $2\mathbf{k}_1 \cdot \mathbf{k}_2 + i\mathbf{s} \cdot (\mathbf{k}_1 \times \mathbf{k}_2)$ in the transition matrix element [1], with $\mathbf{k}_i$ being the c.m.s. pion momenta and $\mathbf{s}$ the nucleon spin. Because of the k^2 dependence of the amplitude, the process is expected to be vanishingly small close to threshold, but of increasing importance at higher energies. Note that, in the expression above, the second term is much smaller than the first one and, hence, should be strongly suppressed in the observables. Also $\mathbf{k}_1 \cdot \mathbf{k}_2$ is symmetric under exchange of indices and again gives pions with $(\pi\pi)_{I=l=0}$. Therefore the usual pion angular distributions are expected to be isotropic in this case, too. However, observables depending strongly on $\mathbf{k}_1 \cdot \mathbf{k}_2$ such as $M_{\pi^+\pi^-}$ and $\delta_{\pi\pi} = \angle(\mathbf{k}_1, \mathbf{k}_2)$ should be strongly influenced by the $p^* \to \Delta\pi$ process, if present.

The process $pp \to \Delta\Delta$, which again should vanish at threshold due to its very strong momentum dependence, is dominated by angular momenta other than $l = 0$ and, hence, provides strongly anisotropic angular distributions for pions and protons [1].

The first four angular distributions shown on the top of Fig. 3 are given in the overall c.m.s. The proton angular distribution $\sigma(\Theta_p)$ exhibits a substantial anisotropy. Following the discussion above, its concave shape is in accordance with heavy meson (σ, ρ) exchange mediating the inelastic pp collision. The π^- angular distribution $\sigma(\Theta_{\pi^-})$, on the other hand, is close to isotropic. This is in favor of a N^* excitation. Here solely the $\Delta\Delta$ process can produce an anisotropy with $\sigma(\Theta_{\pi^-}) \sim 1 + 3\cos^2(\Theta_{\pi^-})$ to leading order [1]. This gives an upper limit of a few percent for a possible contribution from the $\Delta\Delta$ process.

Shown next in Fig. 3 are the angular distributions for the opening angles δ_{pp} and $\delta_{\pi\pi}$ between protons and pions, respectively. Protons emerge predominantly back to back, as expected already by kinematics. However, the pions show also a strong $\cos\delta_{\pi\pi}$ dependence, providing direct evidence for a substantial contribution from the $pp^* \to p\Delta\pi$ process. This finding is supported by the distributions of the pion angles $\hat{\Theta}_{\pi^+}^{p\pi^+}$ and $\hat{\Theta}_{\pi^-}^{p\pi^-}$. (In the following, $\hat{\Theta}_j^{ij}$ denotes the angle of particle j in the c.m.s. of particles i and j, taken relative to the direction of their total momentum in the overall c.m.s., whereas Θ_j^{ij} denotes the corresponding angle relative to the beam direction.) These distributions provide information about Δ excitation in the course of the reaction. Indeed as expected from a p-wave admixture in the $p\pi$ system, the measured distributions show substantial forward peaking. It is stronger in the $p\pi^+$ system, indicating the route $p^* \rightarrow \Delta^{++}\pi^-$ being more favored than the route $p^* \rightarrow \Delta^0\pi^+$. A similar trend is seen in the $M_{p\pi^-}$ and $M_{p\pi^+}$ distributions, where the latter is markedly enhanced towards higher masses.

For a quantitative analysis of the data, we employ MC calculations, where we include now step by step the features discussed above qualitatively. Since these calculations provide no absolute cross sections, they are normalized to the measured total cross section. In Figs. 2 and 3, the differential cross sections are compared to MC simulations of phase space distributions without and with pp final state interactions (FSI) in the Migdal-Watson approximation [17–19] as well as assuming the inelastic pp collision to be mediated by σ exchange. The latter essentially affects only the proton angular distributions, as discussed above. The need for a pp FSI gets obvious from M_{pp}; its inclusion in MC simulations leads to agreement with the data there. This MC simulation is already a very good approximation of the process $pp \rightarrow pp^* \rightarrow pp\sigma$. Because of the large N^* width, the inclusion of the N^* propagator introduces only small changes, most notably in the description of $M_{p\pi^+\pi^-}$. The reasonable description of many of the differential cross sections by this MC simulation is in favor of a dominant s-wave behavior.

However, most notably the $\delta_{\pi\pi}$ and $M_{\pi^+\pi^-}$ distributions still miss a good description. Since these observables are linear in the operator $\mathbf{k}_1 \cdot \mathbf{k}_2$, it is very likely that we see here a clear signature for an admixture of the route $pp \rightarrow pp^* \rightarrow p\Delta\pi \rightarrow pp\sigma$. Indeed, we obtain a substantial improvement in the description of the data, if we coherently add this route with a relative strength of about 25% (expressed by the parameter c) in the ansatz,

$$\mathcal{A} \sim 1 + c\mathbf{k}_1 \cdot \mathbf{k}_2(3D_{\Delta^{++}} + D_{\Delta^0}), \qquad (2)$$

which multiplies the previous expressions for σ exchange (1), FSI, and N^* propagator. Here $D_{\Delta^{++}} = 1/(M_{p\pi^+} - M_{\Delta^{++}} + \frac{i}{2}\Gamma_{\Delta^{++}})$ and, accordingly, D_{Δ^0} are the Δ propagators. This 25% admixture implies that the decay width of $N^* \rightarrow \Delta\pi$ is very small compared to that of $N^* \rightarrow N\sigma$ at energies considered here ($M_{p\pi^+\pi^-} < 1285$ MeV/c^2). However, since the amplitude via $\Delta\pi$ scales as momentum squared, this decay branch will get dominant at high excitation energies. Note that a $\mathbf{k}_1 \times \mathbf{k}_2$ term would lead to very different shapes in $\delta_{\pi\pi}$ and $M_{\pi^+\pi^-}$. The data do not supply any evidence for such a term in agreement with the considerations above. These MC simulations provide now differential distributions, which (up to a scale factor) are very close to those of the much more comprehensive model calculations of Ref. [1]. Since in M_{pp} a substantial pp FSI effect is evident, the calculations of Ref. [1], represented by the solid line in Fig. 1, should be more appropriate. However, they overestimate our data for the total cross section by some factor of 2.

Though the ansatz above is quite successful, the observed asymmetry in the $\hat{\Theta}^{\pi\pi}_{\pi^+}$ angular distribution is not yet described. Also the marked isospin dependence observed in the $p\pi$ system, most notably in $M_{p\pi^+}$ and $M_{p\pi^-}$, is not accounted for. An excellent description of all observables (solid lines in Figs. 2 and 3) is obtained, if we tentatively multiply also the first term with the Δ^{++} propagator in the ansatz,

$$\mathcal{A} \sim (1 + c'\mathbf{k}_1 \cdot \mathbf{k}_2)D_{\Delta^{++}}, \qquad (3)$$

with a bestfit value of $c'\langle k_1 \cdot k_2\rangle = -0.25(4)$. The role of the Δ^{++} propagator with the dominant $N^* \rightarrow N\sigma$ amplitude possibly simulates a strong πN FSI, where one pion from the produced pion pair rescatters on the nucleon giving rise to Δ excitation there. Finally, we note in passing, that the 25% admixture of the $N^* \rightarrow \Delta\pi$ route to the dominant $N^* \rightarrow N\sigma$ route just corresponds on average to that of the four-vector scalar product $(k_{1\mu}k_2^\mu)$, which is Lorentz invariant.

In summary, the first exclusive measurements of $pp \rightarrow pp\pi^+\pi^-$ of solid statistics yield integral cross sections near threshold, which are an order of magnitude below previous data. The pp invariant mass distribution exhibits a clear pp FSI effect. The observed proton angular distribution shows heavy meson exchange to be dominant. The differential cross sections reveal the process—traditionally called the direct decay of the Roper into the σ channel—as the by far dominant one. This process is accompanied by a 25% amplitude of a process, which depends on $\mathbf{k}_1 \cdot \mathbf{k}_2$ and which is traditionally called the decay of the Roper resonance into the $\Delta\pi$ channel. Both processes end up in the same channel $N(\pi\pi)_{I=l=0}$.

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