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Study of baryon and search for dibaryon resonances by the pp → pp$\pi^+\pi^-$ reaction

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Abstract. Exclusive measurements of the two-pion production channel $pp \to pp\pi^+\pi^-$ have been carried out near threshold at CELSIUS with the PROMICE/WASA detector. They reveal $pp \to pp^*(1440) \to pp\sigma \to pp(\pi^+\pi^-)_{I=\ell=0}$ as the dominant process at these energies, however, the data exhibit also significant contributions from $p^*(1440) \to \Delta\pi \to p(\pi^+\pi^-)_{I=\ell=0}$. From the observed interference of these Roper decay routes their relative branching ratio is derived. The status on the search for NN-decoupled $NN\pi$-resonances is reviewed with regard to recent experimental searches in the pionic double charge exchange in nuclei, the two-pion production in nucleon-nucleon collisions, the photo pion-production on the deuteron and the electro pion-production in nuclei.

PACS. 13.75.-n Hadron-induced low- and intermediate-energy reactions and scattering (energy ≤ 10 GeV) – 14.20.Gk Baryon resonances with $S = 0$ – 14.20.Pt Dibaryons – 25.40.Ve Nucleon-induced reactions: Other reactions above meson production thresholds (energies > 400 MeV)

1 Introduction

At the CELSIUS ring the availability of the PROMICE/WASA detector [1] has made it possible to reconstruct complete $pp \to pp\pi^+\pi^-$ events over a large part of phase space for the first time. We have performed exclusive measurements at $T_p = 725, 750$ and 775 MeV [2–4]. With four charged particles in the final state several subsystems may be investigated in great detail. In this contribution we focus on the $N\pi\pi$ and $NN\pi$ subsystems which are of interest for the decay properties of the Roper resonance in its low-energy tail and the search for the dibaryon state d', respectively.

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1.1 The intriguing Roper resonance

In contrast to the $\Delta(1232)$ and other higher-lying resonances the second excited state of the nucleon, the Roper resonance $N^*(1440)$ is still poorly understood both theoretically and experimentally [5]. Being hardly observed in electromagnetic processes and having quantum numbers identical to those of the nucleon, the $N^*(1440)$ has been interpreted as the breathing-mode monopole excitation of the nucleon. Recent theoretical works [6,7] find the Roper excitation to rest solely on meson-nucleon dynamics, whereas another recent investigation [8] proposes it to be actually two resonances with one being the breathing mode and the other one a Δ excitation built on top of the $\Delta(1232)$. In all these aspects the decay modes of the Roper into the $N\pi\pi$ channels play a crucial role. There, the simplest decay is $N^* \to N(\pi\pi)_{I=l=0} := N\sigma$, *i.e.*, the decay into the σ channel. A competitive and, according to present knowledge [5], actually much stronger decay channel is the Roper decay into the $\Delta(1232)$-resonance $N^* \to \Delta\pi$. However, this decay channel is not very well defined, since the Δ is not stable and decays nearly as fast as the Roper does. In fact, most of this decay will end up again in the $N\sigma$ channel and thus will interfere with the direct $N^* \to N\sigma$ decay.

Calculations of the Valencia group [9] predict the $pp \to pp\pi^+\pi^-$ reaction at energies not far above threshold to proceed dominantly via σ exchange in the initial NN collision with successive excitation of the Roper resonance in one of the nucleons. Our first exclusive measurements of this reaction at $T_p = 750\,\mathrm{MeV}$ [2] support very much this perception. This finding suggests $pp \to pp\pi\pi$ to be unique in the sense that it selectively provides the excitation mode "σ" $N \to N^*$ (where "σ" stands now for the σ exchange), which is not accessible in any other basic reaction process leading to the Roper excitation. We exploited this feature to study the decay properties of the Roper resonance in its low-energy tail.

1.2 The evasive dibaryon d′

In QCD-inspired models a large number of dibaryon states of basic $6q$ structure have been predicted [10]. However, despite a vast number of dedicated experiments in search of such states, not a single one could yet be identified unambiguously; for a review see, *e.g.*, [11]. In fact, dibaryons which by their quantum numbers can couple to the NN and/or $N\Delta$ channels cannot be expected to have narrow widths and hence should be hard to sense experimentally. But NN-decoupled dibaryon resonances may be rather narrow, if they are not far above the $NN\pi$ threshold. Indeed, such states at a mass as low as $m = 2.1\,\mathrm{GeV}/c^2$ with $I(J^P) = 0(0^-)$ and $0(2^-)$ have been predicted by Mulders *et al.* [10] though more recent theoretical work taking into account proper antisymmetrization [12] prefers the 0^--state to lie at a somewhat higher mass. Experimental studies for such dibaryon states were carried out in recent years in reactions of the pionic double charge exchange (DCX) in nuclei, in π^0 photoproduction on the deuteron and in direct measurements of 3-particle final-state invariant-mass distributions.

The measurements $A(\pi^+,\pi^-)B$ of the pionic DCX on nuclei exhibit at pion energies below the delta-resonance a peculiar resonance-like structure in the energy dependence of the forward-angle cross-section (fig. 1) [13–15]. This structure has peak cross-sections at incident energies $T_\pi \approx$ 40–60 MeV, *i.e.* far below the Δ excitation. Assuming a narrow $NN\pi$-resonance, the so-called d', with $I(J^P) =$ even (0^-), $m \approx 2.06\,\mathrm{GeV}/c^2$ and $\Gamma_{NN\pi} \approx 0.5\,\mathrm{MeV}$ the DCX data can be very well explained both in their energy and angular dependence.

However, since this reaction takes place in the nuclear medium, subtle medium effects cannot be excluded as origin of this structure. In fact, attempts have been made with some success to describe the observed resonance-like structures for specific nuclei by

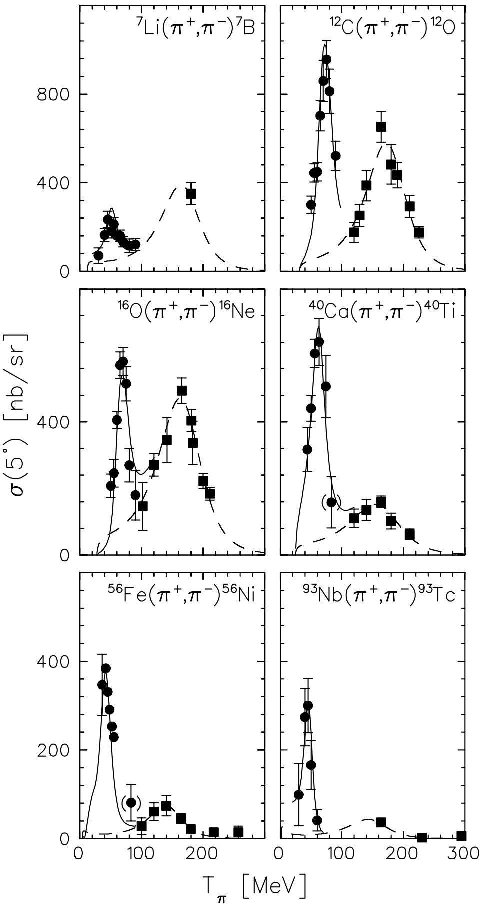

Fig. 1. Energy dependence of the forward-angle cross-section of the pionic DCX on nuclei. The solid lines show calculations assuming the formation of the hypothetical $NN\pi$-resonance d' interfering with the delta excitation (dashed lines) in this process (from ref. [13]).

conventional models [16–18]. In order to minimize the effects of the nuclear medium, the DCX reaction has also been carried out on ^{3}He and ^{4}He [19,20]. However, in these cases there is no longer a bound nuclear state in the exit channel, and the process leads to the nuclear continuum only. Unfortunately, this situation leads to a much less conclusive signature of d' production, in particular, if collision damping of the d'-resonance with the neighboring nucleons is included [19–21].

The search for narrow isoscalar or isovector resonances, which couple to the γd channel has been carried out [22] at MAMI. Deviations $\Delta\sigma$ of the data for the total π^0 production cross-section from a smoothed fit of data is shown in fig. 2. In the range $2020\,\mathrm{MeV}/c^2 < m < 2100\,\mathrm{MeV}/c^2$ no narrow structures have been found on the 3σ level with upper limits in the range of a few microbarn for the production of isoscalar or isovector dibaryons. Yet, this limit is still an order of magnitude above the prediction for d' production [23] and hence not conclusive for this particular dibaryon candidate either.

Therefore, in the search for the d', a hadronic process without medium effects such as the $pp \to pp\pi\pi$ reaction was highly interesting.

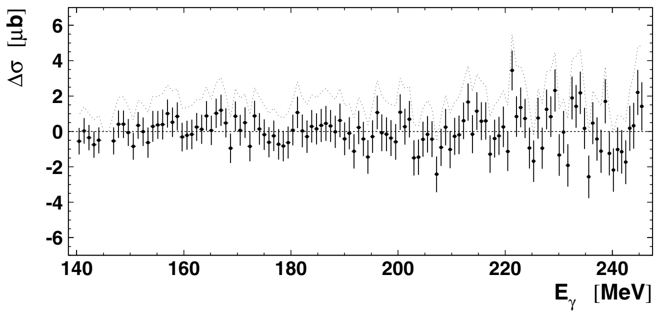

Fig. 2. Deviations $\Delta\sigma$ of the data for the total π^0 photoproduction cross-section on the deuteron. The deviations have been taken relative to a smoothed energy dependence fitted to the data. The dotted curve represents upper limits (90% C.L.) for underlying narrow structures averaged over the experimental energy resolution (from ref. [22]).

2 Experiment

We have carried out exclusive measurements of the $pp \to pp\pi^+\pi^-$ reaction at $T_p = 725, 750$ and $775\,\mathrm{MeV}$ using the PROMICE/WASA setup [1] with a hydrogen cluster jet target at the CELSIUS ring. The ejectiles were detected in the angular range $4^\circ \le \Theta_{\mathrm{lab}} \le 21^\circ$. Protons and pions were identified by the $\Delta E - E$ method, π^+-particles were in addition positively identified by the delayed pulse originating from μ^+ decay following the π^+ decay at rest. This way the two-pion production events could be clearly separated from the huge background of charged ≥ 3-prong events due to single-π^0 production with successive Dalitz decay or γ conversion into e^+e^--pairs. As a test of the energy resolution we constructed the missing-mass spectrum from identified $pp\pi^+$ tracks and obtained a clean single peak at the π^- mass with a width of $\Gamma \approx 8\,\mathrm{MeV}$ FWHM (see fig. 1 in ref. [24]). Eventually the four-momenta of the full $pp\pi^+\pi^-$ events were reconstructed by kinematical fits with one over-constraint (1C) which requires that in the 3-particle missing mass $MM_{pp\pi^+}$ is equal to the pion mass m_{π^-}. About one thousand reconstructed events have been obtained at 725 MeV, whereas for 750 and 775 MeV this number was larger by nearly an order of magnitude.

3 Results and discussion

3.1 Decay routes for the Roper resonance

In fig. 3 we present a selection of the 750 and 775 MeV data [2,4]. To see whether the reaction indeed proceeds via N^* excitation, we inspect the measured distribution of the invariant mass $M_{p\pi^+\pi^-}$. At both energies the data are substantially enhanced towards the high-energy end compared to pure phase space (shaded areas in fig. 3) and compatible with the low-energetic tail of the N^* excitation as reproduced by the appropriate MC simulations. In these simulations the amplitude for the N^* decay is written as

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

which in the full reaction amplitudes complements the propagators for σ exchange and N^* excitation as well as the expression describing the final-state interaction between the outgoing protons in relative s-wave. $D_{\Delta^{++}}$ and D_{Δ^0} are the Δ propagators, the constant 1 stands for the process $N^* \to N\sigma$ and the second term for the decay route $N^* \to \Delta\pi \to N\sigma$, where $\mathbf{k}_1$ and $\mathbf{k}_2$ are the pion momenta. The mixing coefficient c of the two decay routes may be directly read off the data for $M_{\pi^+\pi^-}$ and $\sigma(\delta_{\pi^+\pi^-})$, where $\delta_{\pi^+\pi^-} = \sphericalangle(\mathbf{k}_1, \mathbf{k}_2)$ is the opening angle between the two pions. The latter distribution directly reflects the squared decay amplitude (1) averaged over all possible pion momenta at given $\delta_{\pi^+\pi^-}$, *i.e.*, $\sigma(\delta_{\pi^+\pi^-}) \sim (1 + a\cos\delta_{\pi^+\pi^-})^2$ with $a = c\langle k_1 k_2 (3D_{\Delta^{++}} + D_{\Delta^0})\rangle$, where the brackets denote the average over all possible combinations. For $a \ll 1$ the distribution $\sigma(\delta_{\pi^+\pi^-})$ is essentially linear in a, as exhibited by the data (fig. 3, right column).

In order to illustrate the sensitivity of the data to the mixing of both routes we show calculations for pure phase space, pure transitions $N^* \to N\sigma$ and $N^* \to \Delta\pi \to N\sigma$ as well as mixed scenarios corresponding to $a = -0.20, -0.25$ and -0.33. The negative sign reflects the destructive interference between both routes required by the data.

From a fit to the data the coefficient c can be determined and by this also the ratio $R(M_{N^*})$ of the partial decay widths for the routes $N^* \to \Delta\pi \to N\pi\pi$ and $N^* \to N\sigma$ in dependence of the N^* mass effectively excited in the reaction process. For $T_p = 750\,\mathrm{MeV}$ we have the invariant $N\pi\pi$ mass $\langle M_{N_{\pi\pi}}\rangle = 1264\,\mathrm{MeV}$ and for $T_p = 775\,\mathrm{MeV}$ $\langle M_{N_{\pi\pi}}\rangle = 1272\,\mathrm{MeV}$ with the average taken over the invariant-mass spectra. It is very gratifying for our model that the resulting values of c agree within their statistical errors of about 4%. This leads to branching ratios of $R(1264) = 0.040(4)$ and $R(1272) = 0.060(6)$, respectively. Note the dominance of the $N^* \to N\sigma$ decay route in the low-energy tail of the Roper resonance and the energy dependence of R which is exclusively due to the operators in eq. (1).

Assuming the validity of our model with a fixed value of c we tentatively extrapolate to the nominal Breit-Wigner resonance pole and obtain $R(1440) = 3.9(3)$ which agrees very favorably with the PDG values [5] of 4(2). The model dependence of our result is evident. However, we wanted to demonstrate that the $pp \to pp\pi^+\pi^-$ reaction has the potential to determine experimentally this ratio at the pole with good precision by measurements at appropriate higher energies. This reaction, moreover, provides a tool to map out the energy dependence of the $N^* \to N\pi\pi$ decay by successive increase of the incident proton energy —a program which is currently pursued at CELSIUS/WASA and COSY-TOF.

3.2 Status of the d′ search

The investigation of the $pp \to pp\pi^+\pi^-$ reaction should be a sensitive test of the d' hypothesis, since both invariant-mass spectra $M_{pp\pi^+}$ and $M_{pp\pi^-}$ can be observed simultaneously and the cross-section of the conventional process is small. Since the decay of the hypothetical d'-resonance

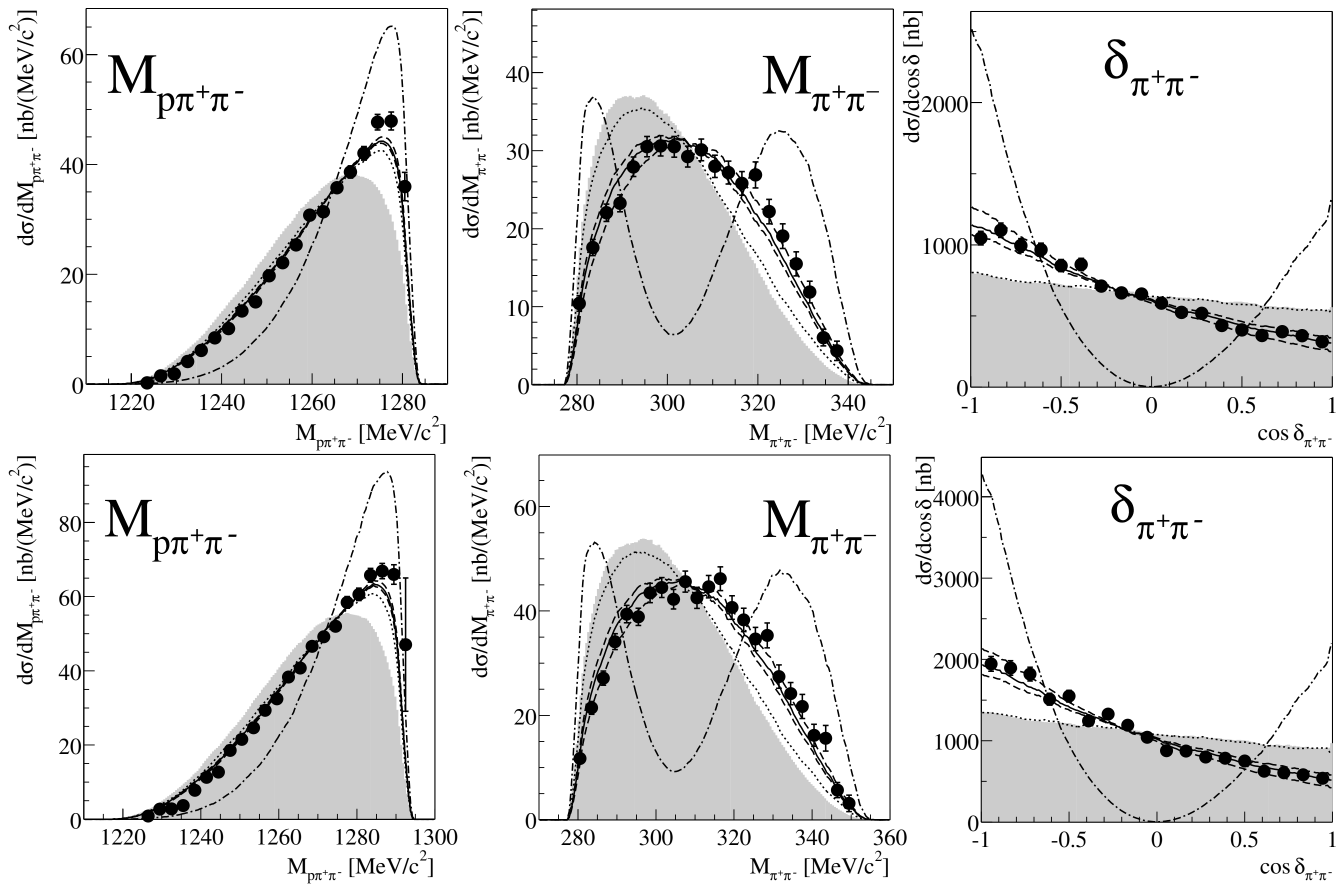

Fig. 3. Influence of the Roper resonance decay onto the differential cross-sections for the invariant masses $M_{p\pi^+\pi^-}$ and $M_{\pi^+\pi^-}$ as well as for the opening angle $\delta_{\pi^+\pi^-}$ between both pions in the reaction $pp \to pp\pi^+\pi^-$ at $T_p = 750\,\mathrm{MeV}$ (top) and $T_p = 775\,\mathrm{MeV}$ (bottom). Pure-phase-space calculations are shown by the shaded area, dotted lines show the case of a pure $N^* \to N\sigma$ decay, whereas the dash-dotted lines exhibit the scenario for a pure $N^* \to \Delta\pi \to N(\pi^+\pi^-)_{I=\ell=0}$ decay. Solid and dashed curves finally show calculations assuming interference from both decay routes with $a = -0.20, -0.25$ and -0.33 [4].

into $pp\pi^-$ is dominated by s-waves between outgoing particles, the two outgoing nucleons (*e.g.* two protons in the decay $d' \to pp\pi^-$) must be in the $^1S_0$-state. In this situation the pp invariant-mass spectrum is strongly affected by the well-known Migdal-Watson–type final-state interaction (FSI) [25,26] leading to a considerable enhancement of the decay rate at small M_{pp}. In order to enhance the sensitivity to d' in $M_{pp\pi^-}$, a cut on small M_{pp} masses, $M_{pp} < 1896\,\mathrm{MeV}/c^2$, has been imposed. In the resulting spectra shown in fig. 4 no narrow structures of statistical significance in $M_{pp\pi^-}$ are observed with the possible exception of an enhancement at $2087\,\mathrm{MeV}/c^2$. Since this data bin is right at the high-energy end of the experimental acceptance range, where instrumental corrections are already substantial and not easily under control, any interpretation of this enhancement would be premature. Its nature can only be solved by measurements at still higher energies. The upper limit (95% C.L.) for the production of narrow dibaryons is of the order $\sigma \lesssim 20\,\mathrm{nb}$ for $m < 2087\,\mathrm{MeV}/c^2$. With respect to d' this upper limit is more than an order of magnitude below the theoretical prediction of $\sigma_{d'} \approx 300$–$1000\,\mathrm{nb}$ [27,28].

We note in passing that in a preceding test run with much lower statistics a structure at $2.063\,\mathrm{GeV}/c^2$ in $M_{pp\pi^-}$ had been observed [24] with a statistical significance of 2 to 3σ depending on the treatment of background. At least part of this bump could meanwhile be associated with a previously unknown detector inefficiency [3,4,29]. We also note that in a measurement [30] of the same reaction at ITEP at $T_p = 920\,\mathrm{MeV}$ a bump has been observed, too, near $2.06\,\mathrm{GeV}$ in $M_{pp\pi^-}$, if a cut on small M_{pp} masses was imposed. To our knowledge, no follow-up studies are under way at ITEP to resolve the nature of that bump.

Finally there are the so-called beam gas data from ARGUS at DESY at $E_e = 5\,\mathrm{GeV}$, which contain the electro pion-production on ^{16}O of the form $\gamma^{*16}\mathrm{O} \to pp\pi^\pm X$. From the measured four-momenta of protons and pions $M_{pp\pi^+}$ and $M_{pp\pi^-}$ spectra have been obtained [31] with and without a constraint on low M_{pp} masses. In both cases the $M_{pp\pi^+}$ data are in accordance with phase space, whereas in $M_{pp\pi^-}$ a bump near $2.06\,\mathrm{GeV}$ is observed with a significance of about 4σ under both conditions. From the analysis of the $M_{p\pi^-}$ spectrum an admixture of misiden-

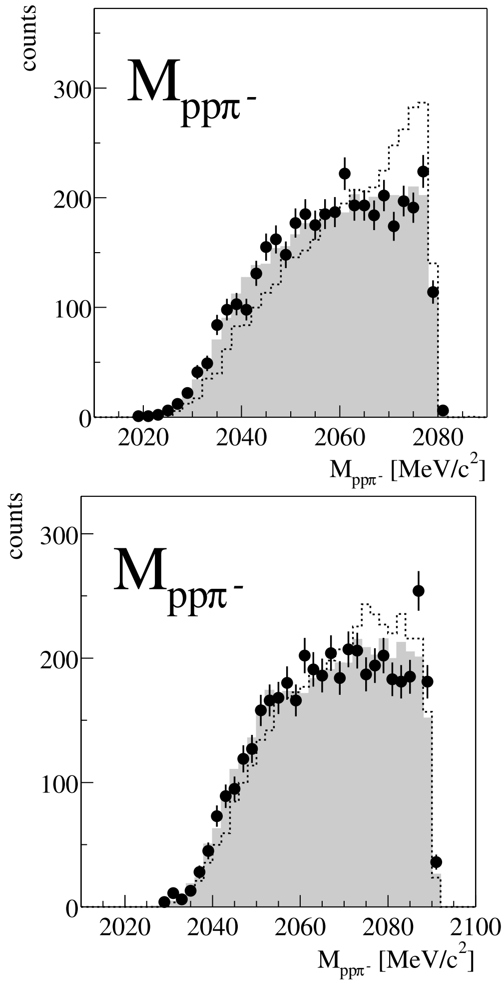

Fig. 4. Invariant-mass spectra $M_{pp\pi^-}$ obtained from the exclusive measurements of the $pp \to pp\pi^+\pi^-$ reaction at $T_p = 750\,\mathrm{MeV}$ (top) and $T_p = 775\,\mathrm{MeV}$ (bottom). The spectra contain only events meeting the condition $M_{pp} < 1896\,\mathrm{MeV}/c^2$ (see text). The dotted lines represent a MC simulation assuming pure phase space for the reaction process, the shaded areas represent a model calculation, which quantitatively describes all differential cross-sections of the reaction (from refs. [3,4, 29]).

tified Λ-particles as a possible reason for this bump can be excluded. For the $M_{pp\pi^-}$ region of the observed bump the corresponding M_{pp} spectrum exhibits an anomalously large pp FSI, in particular in connection with $M_{p\pi^-}$ values around the Λ mass. These findings would be in accordance with what is expected in case of d' production [31]. We note that the $M_{pp\pi^-}$ spectra constructed from $pp\pi^-\pi^\pm$ and $pp\pi^-\pi^+\pi^+$ event samples do not show any enhancements near 2.06 GeV —again as expected in case of d' electroproduction on a np-pair, since in this case there is only single-pion production. π^0-particles were not identified, hence their possible accompanying production cannot be excluded.

4 Conclusions

The kinematically complete, even overdetermined $pp \to pp\pi^+\pi^-$ data have enabled us to analyze several observables in great detail. This way we were able to demonstrate that the Roper resonance is excited by σ exchange in pp collisions. Furthermore we studied two interfering decay routes into the $N\pi\pi$ final channel. The ratio of the partial widths for decay via $\Delta\pi$ and $N\sigma$ was shown to be $R = 0.04$ and $R = 0.06$ at invariant masses of 1264 and 1272 MeV, respectively, within our model ansatz. Ongoing experiments at COSY-TOF and CELSIUS/WASA will test this ansatz at higher energies and see if our extrapolation to the Roper pole is justified.

In recent years high-statistics and high-resolution experiments have been carried out in search for a possible signature of d' in basic systems. In $\gamma d \to \pi^0 X$ and in $pp \to pp\pi^+\pi^-$ no narrow structures of statistical significance have been found. In the former reaction the deduced upper limits are still above the predicted d' production cross-sections; however, for the latter reaction they are below the predicted values by already one to two orders of magnitude. Together with the findings on nuclei (DCX, $\gamma^{*16}\mathrm{O} \to pp\pi^\pm X$) our results on the basic systems imply a number of consequences. Either d' does not exist at all, or its production cross-section in $pp \to pp\pi^+\pi^-$ is for some unknown reason much smaller than expected, or its mass outside the nuclear medium is above the mass range investigated so far, or it possibly exists only in the presence of the nuclear medium.

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