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The $pp\rightarrow pp\pi^+\pi^-$ reaction studied in the low-energy tail of the Roper resonance

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Exclusive measurements of the $pp\rightarrow pp\pi^+\pi^-$ reaction have been carried out at $T_p=775$ MeV at CELSIUS using the PROMICE/WASA setup. Together with data obtained at lower energy, they point to a dominance of the Roper excitation in this process. From the observed interference of its decay routes $N^*\rightarrow N\sigma$ and $N^*\rightarrow\Delta\pi\rightarrow N\sigma$, their energy-dependent relative branching ratio is determined.

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The Roper resonance $N^*(1440)$ with $I(J^P)=1/2(1/2^+)$ is presently known as the second excited state of the nucleon [1]. In contrast to the first excited state, the $\Delta(1232)$, and also higher-lying resonances, the $N^*(1440)$ is still poorly understood both theoretically and experimentally. Since it is hardly excited by electromagnetic probes and has the same quantum numbers as the nucleon, it has been interpreted as the breathing mode monopole excitation of the nucleon. A recent theoretical work [2,3] finds the Roper excitation to rest solely on meson-nucleon dynamics, whereas another recent investigation [4] proposes it to be actually two resonances with one being the breathing mode and the other one a Δ excitation built on top of $\Delta(1232)$. In all these aspects the decay modes of the Roper resonance into the $N\pi\pi$ channel play a crucial role. The simplest decay is $N^*\rightarrow N(\pi\pi)_{I=l=0}:=N\sigma$, i.e., the decay into the σ channel. A competitive and, according to present knowledge [1], actually much stronger decay channel is the sequential Roper decay via the $\Delta(1232)$ resonance, $N^*\rightarrow\Delta\pi$. However, this decay channel is not very well defined, in particular not orthogonal to the $N\sigma$ channel, since the Δ is also unstable 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 $N^*\rightarrow N\sigma$ decay.

In a previous work, the first exclusive measurement of the $pp\rightarrow pp\pi^+\pi^-$ reaction at $T_p=750$ MeV [5], we have shown that at energies not far above threshold this reaction can be well described by dominant σ exchange in the initial NN collision with subsequent excitation of the Roper resonance in one of the nucleons. This result, which is in agreement with theoretical predictions of the Valencia group [6], exhibits this reaction to be unique in the sense that it selectively provides the excitation mode ''σ'' $N\rightarrow N^*$ (where "σ" stands for the σ exchange), which is not accessible in any other basic reaction process leading to the Roper excitation.

In this work we present new data from an exclusive measurement of the $pp\rightarrow pp\pi^+\pi^-$ reaction at $T_p=775$ MeV. Together with the data at $T_p=750$ MeV, they are analyzed with particular emphasis on the interference of the decay routes $N^*\rightarrow N\sigma$ and $N^*\rightarrow\Delta\pi\rightarrow N\sigma$. The data have been taken at the CELSIUS storage ring using the PROMICE/WASA detector with a cluster jet H_2 target [7]. Protons and π^+ particles have been registered in the forward detector part covering the polar angles $4°\leqslant\Theta_{Lab}\leqslant 21°$. The particles have been identified by the $\Delta E-E$ method, the stopped π^+ particles in addition by their delayed pulse from subsequent muon decay. From the measured four-momenta of the two registered protons and the identified π^+, the full $pp\pi^+\pi^-$ events have been reconstructed by kinematical fits with one overconstraint. Detector efficiencies and acceptance have been obtained from Monte Carlo (MC) simulations of the detector response [8]. The absolute normalization of the data has been obtained by monitoring the luminosity of the experiment by the simultaneous measurement of the elastic scattering and its comparison to data from literature [9]. The total cross section for the $pp\rightarrow pp\pi^+\pi^-$ reaction obtained for $T_p=775$ MeV is $\sigma_{tot}=2.2(5)$ μb and shown in Fig. 1, together with previous results [5,10–15]. Our value is an order of magnitude below the bubble chamber results [13], in agreement with our findings at lower energies [5]. The estimated uncertainty of about 20% is due to [8] statistical uncertainties in the collected pp elastic (1%) and $pp\pi^+\pi^-$ (5%) events as well as systematic uncertainties in the selection of pp elastic (8%) and $pp\pi^+\pi^-$ (12%) events, uncertainty in the lifetime of the data acquisition system (8%), and uncertainties in the extrapolation to full solid angle (6%). For $T_p=750$ MeV, we show two values for σ_{tot}. The upper one

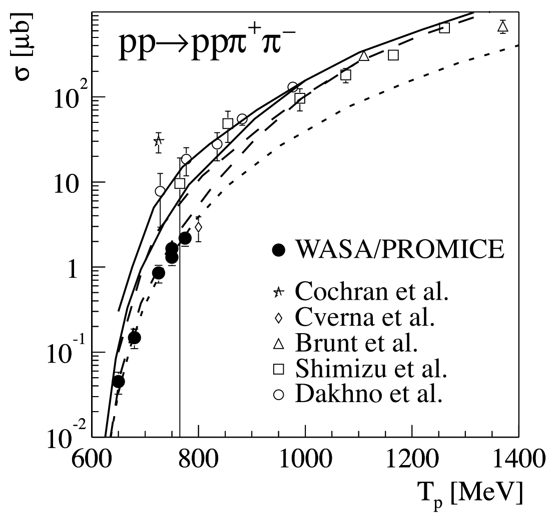

FIG. 1. Energy excitation function of the integral cross section of the $pp \rightarrow pp\pi^+\pi^-$ reaction. The WASA/PROMICE data (black points) from this work and Ref. [5] are compared with previous data (open symbols) [10–15] and predictions [6] with two different parameter sets (solid and dashed lines), with and without pp final-state interaction (upper and lower lines, respectively) and a phase space distribution adjusted to our data (dotted line).

is the previously published value [5], the lower one has been derived from a subsample of those data using the same event selection criteria as applied now for the 775-MeV data. In order to test the robustness of the analysis, the event selection criteria have been slightly modified compared to the ones used previously [5]. However, within uncertainties both values agree with each other.

Differential cross sections are shown in Figs. 3–5, which will be discussed in the following. As pointed out in Ref. [5], the proton angular distribution in the overall center of mass system (cms) is governed by the meson exchange between the colliding protons. In particular, it should be described by σ exchange leading to $\sigma(\Theta_p) \sim 1 - a\cos^2(\Theta_p)$, with $a > 0$ given by the amplitude for σ exchange, while $a < 0$ would be typical for π exchange. The data at $T_p = 750$ MeV were well described by this *Ansatz*. This holds also for the new data at $T_p = 775$ MeV [8]. Instead of looking at the angular distribution in the overall cms, it appears more instructive to look at the angular distributions in the pp subsystem. The definition of angles is illustrated in Fig. 2. Let us denote the scattering angles of particles 1 and 2 in the overall cms by Θ_{p_1} and Θ_{p_2}, respectively, and the scattering angle of the center of mass motion of both protons (summed momenta) in the overall cms by $\Theta_{p_1 p_2}$. Within the rest frame of the two particles ($p_1 p_2$ subsystem) the two angles can be defined as the scattering angle of p_2 either with respect to the beam axis, $\Theta_{p_2}^{p_1 p_2}$, or with respect to the summed momenta of p_1 and p_2 in the overall cms. The latter angle is denoted by $\hat{\Theta}_{p_2}^{p_1 p_2}$. Note that due to the indistinguishability of the two protons, all these angular distributions have to be symmetric about 90°. Since in this reaction the two protons are emitted dominantly back to back in the overall cms (see distributions of the opening angle δ_{pp} between the two protons in Refs. [5,8]), the Θ_p^{pp} distribution (Fig. 3) is very close to the Θ_p distribution and hence also exhibits a $(1 - a\cos^2\Theta_p^{pp})$ dependence. Shown in Fig. 3 is, in addition, the $\hat{\Theta}_p^{pp}$ distribution. This distribution reflects the scattering situation of the two protons within their subsystem. The observed distribution is isotropic, i.e., we indeed see the outgoing protons to be in relative s wave, as anticipated in Ref. [5].

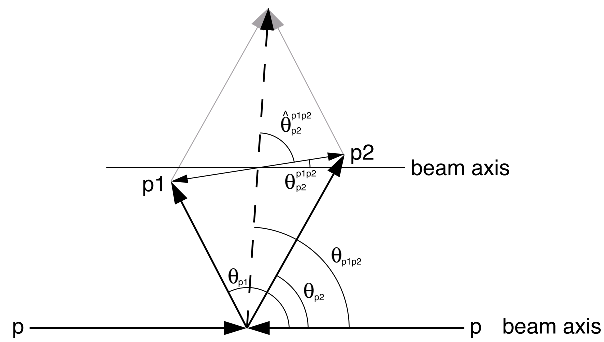

FIG. 2. Definition of the different scattering angles in the subsystem of particles, here for the case of two particles ($p1$,$p2$) resulting from the reaction in the overall center of mass system. For simplicity, the figure shows a nonrelativistic construction. The other particles are not shown. For details, see text.

We note in passing that also the pion angular distribution in the overall cms [8] is flat as well—as was the case at $T_p = 750$ MeV, too. Since here only the process $NN \rightarrow \Delta\Delta \rightarrow NN\pi\pi$ leads to nonisotropic angular distributions [5,6,8], we conclude that this process, which is expected to contribute substantially at energies $T_p > 1000$ MeV [6], is not yet of relevance at $T_p = 775$ MeV.

To see whether the reaction proceeds via N^* excitation, we inspect the measured distribution of the $p\pi^+\pi^-$ invariant mass $M_{p\pi^+\pi^-}$ (Fig. 4). Compared to phase space, the data are substantially enhanced near the high-energy end, compatible with the low-energy tail of the N^* excitation and reproduced by the appropriate calculations for N^* excitation, as will be discussed in detail below. As in Ref. [5], we conclude that the process "σ"$N \rightarrow N^*$ is indeed the one which drives the reaction $pp \rightarrow pp\pi^+\pi^-$ at the energies considered here.

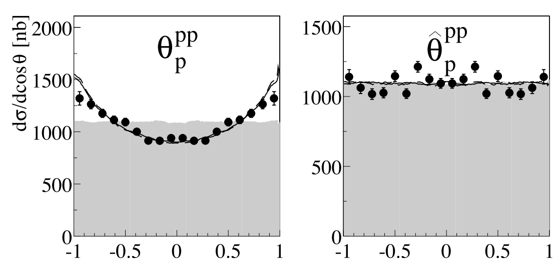

FIG. 3. Proton angular distributions in the pp subsystem at $T_p = 775$ MeV. In the left diagram the proton emission angle Θ_p^{pp} is taken relative to the protons' summary momentum in the overall cms. Shaded areas give the phase space distribution, whereas dashed and solid lines show MC simulations according to *Ansätze* (1) and (2), respectively.

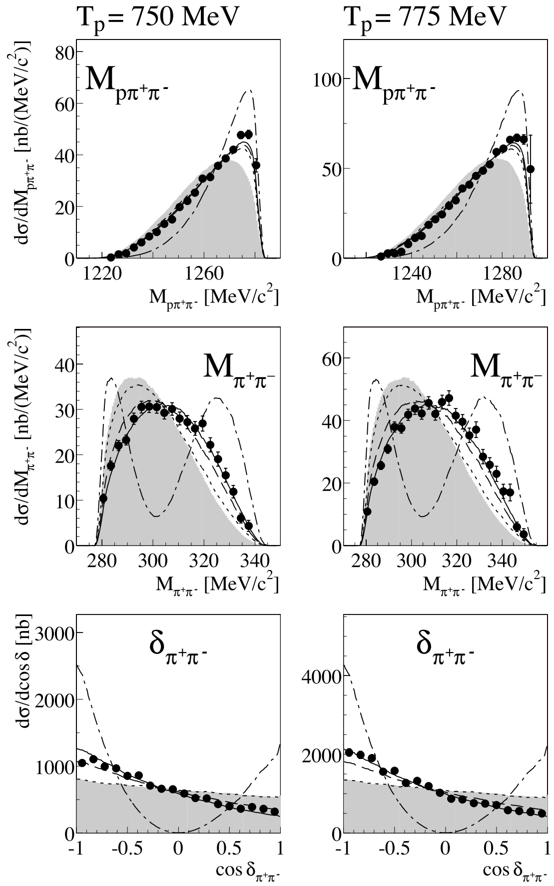

FIG. 4. Invariant masses $M_{p\pi^+\pi^-}$ and $M_{\pi^+\pi^-}$ as well as the opening angle $\delta_{\pi^+\pi^-}$ between the two pions for both 750 (left) and 775 MeV (right) beam energies. The data are shown in comparison to phase space (shaded area) and MC simulations for pure decays $N^* \rightarrow N\sigma$ (dotted), $N^* \rightarrow \Delta\pi$ (dashed dotted), and their interference with $c' = -37$ (dashed) and -61 (solid) $(\mathrm{GeV}/c)^{-2}$ using Eq. (2).

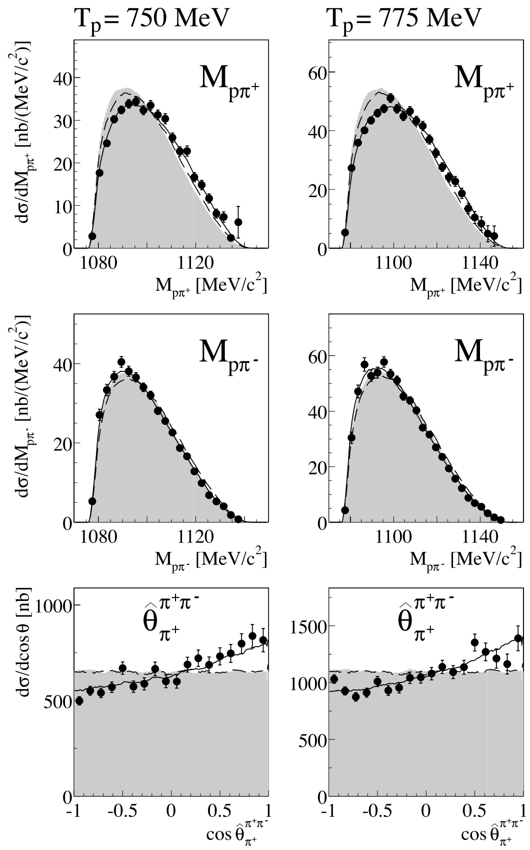

FIG. 5. Invariant masses of $p\pi^+$ and $p\pi^-$ systems (top and middle) as well as scattering angle of the π^+ in the $\pi\pi$ system with respect to the summed pion momenta (bottom). The left side shows the results for 750 MeV and the right one for 775 MeV. The shaded areas give phase space distributions, whereas dashed and solid lines show MC simulations according to *Ansätze* (1) and (2), respectively.

We now examine the N^* decay process as exhibited by the data. In the analysis of the 750-MeV data, two versions for the N^* decay amplitude have been proposed [5]:

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

and

$$\mathcal{A} \sim (1 + c'\mathbf{k}_1 \cdot \mathbf{k}_2) D_{\Delta^{++}}. \tag{2}$$

In the full reaction amplitude, this factor $\mathcal{A}$ complements the propagators for σ exchange and N^* excitation as well as the expression describing the final-state interaction between the two outgoing protons in relative s wave. Here $D_{\Delta^{++}} = 1/[M_{p\pi^+} - M_{\Delta^{++}} + (i/2)\Gamma_{\Delta^{++}}]$ and D_{Δ^0} defined analogously are the Δ propagators. The constant 1 stands for the process $N^* \rightarrow N\sigma$ and the scalar product $\mathbf{k}_1 \cdot \mathbf{k}_2$ of the pion momenta $\mathbf{k}_1$ and $\mathbf{k}_2$ for the double p-wave decay of the route $N^* \rightarrow \Delta\pi \rightarrow N\sigma$. For simplicity, we have neglected the spin flip term $i\mathbf{s} \cdot (\mathbf{k}_1 \times \mathbf{k}_2)(3D_{\Delta^{++}} - D_{\Delta^0})$ in this decay channel, with $\mathbf{s}$ being the nucleon spin. This term describes the transition $N^* \rightarrow \Delta\pi \rightarrow N(\pi\pi)_{I=l=1}$. It does not interfere with the other terms, is smaller than the $\mathbf{k}_1 \cdot \mathbf{k}_2$ term by a factor of 16 in the cross section, and hence does not influence significantly the conclusions in this paper. Whereas in Refs. [5,6] this scalar product has been calculated in the overall cms, we here use the more appropriate N^* system. We note, however, that the difference is tiny, since near threshold the static limit approximation is reasonably valid.

Ansatz (1) represents the leading term of the two-pion decay of the Roper resonance as worked out by the Valencia group [6]. The constant c [and correspondingly, c' in *Ansatz* (2)] gives the relative strength between the two decay routes and is treated in the following as the parameter to be adjusted to the data, which will enable us to deduce the relative branching ratio of the two decay routes in question. With c being adjusted appropriately, we get a quantitative description of the data both for $T_p = 750$ MeV [5] and 775 MeV (see Figs. 3–5) with the exception of the distributions for the invariant masses $M_{p\pi^+}$, $M_{p\pi^-}$, and $\hat{\Theta}^{\pi^+\pi^-}_{\pi^+}$ (dashed lines in Fig. 5). As shown in Ref. [5], *Ansatz* (2) is able to make up for this deficiency (solid lines in Fig. 5) without destroying the good agreement in the other observables. We admit, however, that Eq. (2) having the Δ propagator multiplying also the constant term, is a purely phenomenological *ad hoc Ansatz*. Apparently it is successful, but its physical content is not (yet) fully understood. As suggested in Ref. [5], it possibly accounts effectively for some final-state interaction effect. Whereas in *Ansatz* (1) the parameter c is defined as energy independent, since all dynamics is taken into account explicitly, the situation is not so clear with our phenomenological *Ansatz* (2); if some final-state interaction is absorbed here, an energy dependence of c' cannot be excluded *a priori*.

In Fig. 4 we compare calculations assuming different mixing scenarios for the two N^* decay routes to the data for those observables which are most sensitive to the N^* decays. Shown are the distributions of invariant masses $M_{p\pi^+\pi^-}$ and $M_{\pi^+\pi^-}$ as well as $\delta_{\pi^+\pi^-} = \sphericalangle(\mathbf{k}_1,\mathbf{k}_2)$, i.e., the opening angle between the two pion momenta in the overall cms. The latter distribution directly reflects the squared decay amplitudes (1) and (2), respectively, averaged over all possible moduli of pion momenta at given $\delta_{\pi^+\pi^-}$, i.e., $\sigma(\delta_{\pi^+\pi^-}) \sim (1+b\cos\delta_{\pi^+\pi^-})^2$ with the mixing coefficient b.

In case of Eq. (2) we have $b=c'\langle k_1k_2\rangle$ where the brackets denote the average over all possible combinations. For $b\ll 1$ the distribution $\sigma(\delta_{\pi^+\pi^-})$ is essentially linear in b, whereas this dependence gets quadratic for $b\gg 1$. Shown in Fig. 4 are calculations for pure phase space and for transitions via either the $N^*\to N\sigma$ route $(b=0)$ or the $N^*\to\Delta\pi\to N\sigma$ route. In order to illustrate the sensitivity of the data to the mixing of both routes, calculations are also shown with $c'=-37$ and $-61\ (\mathrm{GeV}/c)^{-2}$ corresponding to $b=-0.20$ and -0.33, respectively, at $T_p=750$ MeV. The negative sign of the coefficients reflects the destructive interference between both terms, which is required by the data. If we fit b for best reproduction of the data, we obtain $b=-0.27(2)$ for $T_p=750$ MeV and $b=-0.32(1)$ for $T_p=775$ MeV, or $c'=-50(4)$ and $-53(3)(\mathrm{GeV}/c)^{-2}$, respectively. Both values agree within their uncertainties, as they should if c' is energy independent; i.e., we not only observe the proper dependence in the angle $\sphericalangle(\mathbf{k}_1,\mathbf{k}_2)$, but also in the energy implied by k_1k_2 as the beam energy is changed, and with it the energy of the N^* excitation: for $T_p=750$ MeV we have $\langle M_{N^*}\rangle=1264$ MeV and for $T_p=775$ MeV the average value is $\langle M_{N^*}\rangle=1272$ MeV.

Alternatively, if we use Eq. (1) for the description of the data, we arrive at $c=1.88(8)$ and $1.96(8)(\mathrm{GeV}/c)^{-1}$ for $T_p=750$ and 775 MeV, respectively.

Having fitted the parameters c and c', respectively, we can determine the ratio 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 excited N^* mass by

$$R(M_{N^*}) := \frac{\Gamma_{N^*\to\Delta\pi\to N_{\pi\pi}}(M_{N^*})}{\Gamma_{N^*\to N\sigma}(M_{N^*})} = \frac{9}{8}\ c^2\ \ (\text{or}\ \ c'^2)\frac{\int |\mathcal{M}_{\Delta\pi}|^2 dM^2_{p\pi^+}dM^2_{\pi^+\pi^-}}{\int |\mathcal{M}_{N\sigma}|^2 dM^2_{p\pi^+}dM^2_{\pi^+\pi^-}} \quad (3)$$

TABLE I. Ratio of the branching ratios for the decays $N^*\to\Delta\pi\to N\pi\pi$ and $N^*\to N\sigma$ in dependence of the excited N^* mass using *Ansätze* (1) and (2), respectively, for the analysis of the data at $T_p=750$ and 775 MeV. The extracted parameters c and c' are given in units of $(\mathrm{GeV}/c)^{-1}$ and $(\mathrm{GeV}/c)^{-2}$, respectively.

	Eq. (1)	Eq. (2)
c or c' ($T_p=750$ MeV)	1.88(8)	−50(4)
c or c' ($T_p=775$ MeV)	1.96(9)	−53(3)
$R(1264)$ ($T_p=750$ MeV)	0.034(4)	0.030(5)
$R(1272)$ ($T_p=775$ MeV)	0.054(6)	0.047(5)
$R(1371)$ Extrapolated	1.0(1)	0.6(1)
$R(1440)$ Extrapolated	3.4(3)	1.1(2)
$R(1440)$ Particle Data Group [1]	4(2)	

with the matrix elements $\mathcal{M}_{N\sigma}=1$ and $\mathcal{M}_{\Delta\pi}=\mathbf{k}_1\cdot\mathbf{k}_2(3D_{\Delta^{++}}+D_{\Delta^0})$ in case of Eq. (1). In case of Eq. (2), these matrix elements are $\mathcal{M}_{N\sigma}=D_{\Delta^{++}}$ and $\mathcal{M}_{\Delta\pi}=\mathbf{k}_1\cdot\mathbf{k}_2 D_{\Delta^{++}}$. Note that the integral is just the integration of the matrix element squared over the Dalitz plot in dependence of the invariant masses $M^2_{p\pi^+}$ and $M^2_{\pi^+\pi^-}$. The factor 9/8 in Eq. (3) is determined by isospin coupling coefficients and accounts for the decay into channels other than $p(\pi^+\pi^-)_{I=l=0}$. If we neglect spin flip contributions, then 2/3 of both the $p^*\to p\sigma$ decay and of the $p^*\to\Delta\pi$ decay end up in the $p\pi^+\pi^-$ channel, i.e., the correction factor is unity instead of 9/8.

The results of these calculations are given in Table I. For $T_p=750$ MeV and $T_p=775$ MeV, both equations lead to ratios $R(M_{N^*})$ which agree within uncertainties. In this low-energy tail of the Roper resonance, the ratio turns out to be very small and strongly energy dependent as expected from the $\mathbf{k}_1\cdot\mathbf{k}_2$ dependence of $M_{\Delta\pi}$. We find $R(1272)\approx 1.5R(1264)$, i.e., a 50% relative increase in the $N^*\to\Delta\pi$ route at the higher energy. This increase is essentially due to the increase of $\langle k_1k_2\rangle^2$, which increases by more than 40% by the 25-MeV increase in the beam energy. The additional energy dependence in the $N^*\to\Delta\pi$ route due to the Δ propagator in *Ansatz* (1) is still of minor importance here. In case of *Ansatz* (2), such a small energy dependence could be compensated easily by a small variation in the parameter c' within its statistical uncertainty. Hence with regard to this point the two datasets at 750 and 775 MeV are not yet able to discriminate between both equations.

However, the different appearance of the Δ propagator in Eqs. (1) and (2) will get discriminative if we go to higher energies. To demonstrate this we extrapolate $R(M_{N*})$ to the nominal resonance pole at 1440 MeV/c^2, assuming Eqs. (1) and (2) to hold also at higher energies and taking for c and c' the average of the values obtained at $T_p = 750$ and 775 MeV. The different appearance of the Δ propagators in Eqs. (1) and (2) now leads to very different values. In the case of the conventional *Ansatz*, Eq. (1), we get $R(1440) = 3.9(3)$; which is well within the range of the PDG values of 4(2) [1]. In case of Eq. (2), the difference in the energy dependence of the two decay routes is much smaller, and we obtain only $R(1440) = 1.3(2)$. We note in passing that due to the strong energy dependence of this ratio, also the appropriate pole position is crucial. If instead of the nominal Breit-Wigner mass pole position we use the pole position evaluated from the speed plot of πN phase shifts, namely, $M_{N*} = 1371$ MeV/c^2 [1,2], then the values for the ratio decrease to 1.2(1) and 0.7(1), respectively, using Eqs. (1) and (2).

In summary, the new set of differential data for the $pp \to pp\pi^+\pi^-$ reaction at $T_p = 775$ MeV supports the conclusion that this reaction is dominated by the excitation of the Roper resonance and its decay into the $N\pi\pi$ channels as derived recently [5] from the analysis of the first exclusive measurement at $T_p = 750$ MeV. The new dataset gives a first experimental evidence for a different energy dependence of the decay routes $N^* \to \Delta\pi$ and $N^* \to N\sigma$. The decay branching of $N^* \to \Delta\pi$ increases by 50% relative to that of $N^* \to N\sigma$, when increasing the incident proton energy from $T_p = 750$ MeV to 775 MeV, or equivalently, when increasing the effective $N\pi\pi$ mass from $M_{N*} = 1264$ to $M_{N*} = 1272$. In this very low energy tail of the Roper resonance, we find the $N^* \to N\sigma$ decay to be clearly dominant with $R(1264) \cong 0.04$ and $R(1272) \cong 0.06$. These results are independent of the *Ansatz* used for the reaction amplitude. Though we observe the low-energy region to be represented very well by a $N\sigma$ partition—as suggested, e.g., in Ref. [2]—we also see a small but rapidly increasing influence of the $\Delta\pi$ partition. Due to its $k_1 \cdot k_2$ dependence the $N^* \to \Delta\pi$ route is even likely to finally take over at higher energies. Extrapolating to the resonance pole we obtain $R(1440) = 3.4(3)$ and 1.1(2) using *Ansätze* (1) and (2), respectively. Clearly, this extrapolation is strongly model dependent. However, as we have demonstrated, the $pp \to NN\pi\pi$ reaction offers the opportunity to experimentally map out the energy dependence of the $N^* \to N\pi\pi$ decay systematically up to the resonance pole by successively increasing the incident proton energy—a program that is currently pursued at the CELSIUS-WASA.

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