THE ROPER RESONANCE $N^*(1440)$ IN NUCLEON–NUCLEON COLLISIONS AND THE ISSUE OF DIBARYONS*

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In many reactions leading to excitations of the nucleon, the Roper resonance $N^*(1440)$ can be sensed only very indirectly by complex partial-wave analyses. In nucleon–nucleon collisions the isoscalar single-pion production as well as specific two-pion production channels present the Roper excitation free of competing resonance processes at a mass of 1370 MeV and a width of 150 MeV. A detailed analysis points to the formation of $N^*(1440)N$ dibaryonic systems during the nucleon–nucleon collision process similar to what is known from the $\Delta(1232)N$ threshold.

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Dedication

This paper is dedicated to the 90$^{\mathrm{th}}$ birthday of L. David Roper, who discovered the famous Roper resonance in the nucleon.

1. Introduction

The $N^*(1440)$ resonance has been a puzzle ever since its discovery in πN phase shifts by L.D. Roper in 1964 [1]. In most respective investigations, no apparent resonance signatures show up directly in the observables, but have to be revealed by sophisticated partial-wave analyses. Its resonance parameters show still quite some scatter in its values [2]. Also, its nature has been a matter of a permanent debate. The finding that it is in principle of a two-pole structure [3] increases its complexity discussed in many subsequent studies [4–7]. Since the quantum numbers of $N^*(1440)$ are identical to those of the nucleon, it has also been associated with the breathing mode of the nucleon.

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Whereas for most resonances the values for the pole position obtained in partial-wave analyses on the one hand and for the resonance mass and width obtained by Breit–Wigner fits on the other hand are very close, the situation is totally different for the Roper resonance. Recent phase-shift analyses of πN and γN data show the pole of the Roper resonance to be about 70 MeV below its canonical value of 1440 MeV. In PDG, its pole position is presently quoted to be in the range of 1360–1380 (≈ 1370) MeV (real part) and 180–205 (≈ 190) MeV ($2\times$ imaginary part), whereas its Breit–Wigner mass and width are estimated to be in the range $m = 1410$–1470 (≈ 1440) MeV and 250–450 (≈ 350) MeV [2].

In nucleon–nucleon and nucleon–nucleus collisions, the $N^*(1440)$ excitation usually sits on top of a substantial background, which cannot be removed easily nor reliably calculated. In the αp experiment at Saclay [8], a bump representing the Roper excitation is observed at $m = 1390(20)$ MeV with $\Gamma = 190(30)$ MeV in the missing mass spectrum, however, still sitting on a large background. Hence, the detailed resonance parameters depend substantially on the treatment of the background as demonstrated, *e.g.*, in Ref. [10]. Analyses of high-energy pp scattering give similar values for the Roper excitation [11].

2. Isoscalar single-pion production in NN collisions

The beauty of isoscalar single-pion production is that the usually overwhelming Δ excitation is eliminated by isospin selection in this process. Hence, the excitation of the next higher-lying resonance, the Roper resonance, can be observed free of any resonance background. The total cross section of isoscalar single-pion production can be obtained from that of the purely isovector reaction $pp \to pp\pi^0$ and that of the isospin-mixed reaction $pn \to pp\pi^-$ by the isospin relation

$$\sigma_{pn\to NN\pi}(I=0) = 3\left(\sigma_{pn\to pp\pi^-} - 1/2\ \sigma_{pp\to pp\pi^0}\right) . \tag{1}$$

Both reactions have been measured exclusively and kinematically complete (with overconstraints) by WASA-at-COSY in the energy range $T_p =$ 1.0–1.35 GeV ($\sqrt{s} = 2.3$–2.45 GeV) [12, 13]. Figure 1 shows the energy dependence of the total cross section of the $pn \to pp\pi^-$ reaction from threshold up to $\sqrt{s} = 2.5$ GeV. Plotted are all available data from previous measurements together with the WASA results, which are given by the full (red) dots.

Starting from threshold, we observe a strongly rising cross section, which may be associated with t- and s-channel Δ excitation [13]. Around $\sqrt{s} =$ 2.2. GeV, the cross section levels off somewhat before starting to rise again towards higher energies. Such a rise is expected from the excitation of the

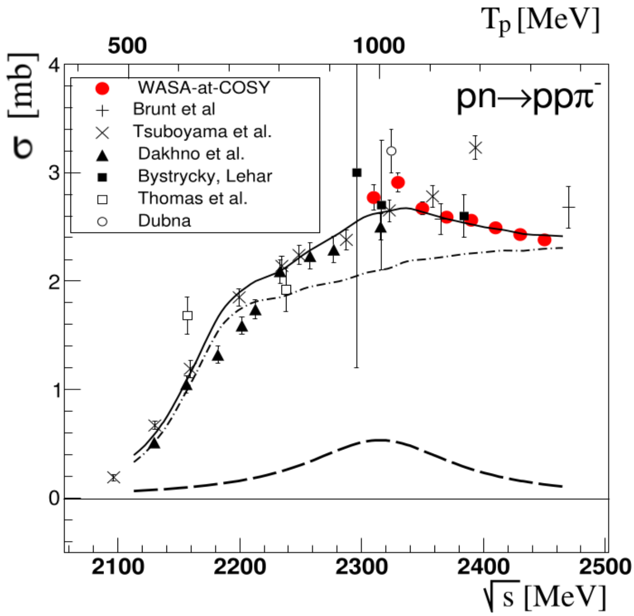

Fig. 1. Energy dependence of the total cross section for the $pn \to pp\pi^-$ reaction. Full (red) dots represent results from WASA-at-COSY [12], other symbols denote results from earlier works [14–19]. The dash-dotted line shows the isovector contribution. The dashed curve at the bottom gives a Breit–Wigner fit to the difference between the dash-dotted curve and the data for the $pn \to pp\pi^-$ reaction. The solid line gives the sum of dashed and dash-dotted curves. From Ref. [13].

Roper resonance. However, what is unexpected is that the cross section starts falling again beyond $\sqrt{s} = 2.3$ GeV leading thus to a pronounced bump structure in the total cross section.

The dash-dotted curve shown in Fig. 1 represents a fit to corresponding data for the $pp \to pp\pi^0$ reaction (see Fig. 3 in Ref. [13]) and gives its total cross section divided by two, *i.e.*, it represents just the isovector contribution to the $pn \to pp\pi^-$ channel. The difference of the dash-dotted curve to the total cross section of the $pn \to pp\pi^-$ reaction can be well represented by a Breit–Wigner curve with $m = 2310$ MeV and $\Gamma = 150$ MeV plotted by the dashed curve at the bottom of Fig. 1. According to Eq. (1), this dashed curve represents now the isoscalar cross section of single-pion production divided by three. The full curve in Fig. 1 is just the sum of dashed and dash-dotted curves reproducing the data of the $pn \to pp\pi^-$ reaction reasonably well.

Figure 2 displays the deduced isoscalar single-pion production cross section together with all available previous data [15, 16, 20, 21], in particular also with the results of the partial-wave analyses of Ref. [22], which are plotted in Fig. 2 by open crosses surrounded by a hatched band indicating the uncertainties. As in Fig. 1, a Breit–Wigner fit is displayed with $m = 2310$ MeV and $\Gamma = 150$ MeV. For comparison, we also show the expected energy dependence of a conventional t-channel excitation of the Roper resonance with a subsequent p-wave pion emission [12], arbitrarily normalized to the data point at $\sqrt{s} = 2260$ MeV. Due to the strong energy dependence of the p-wave emission, we would have expected a steeply increasing cross section — similar to what is observed for the Δ excitation.

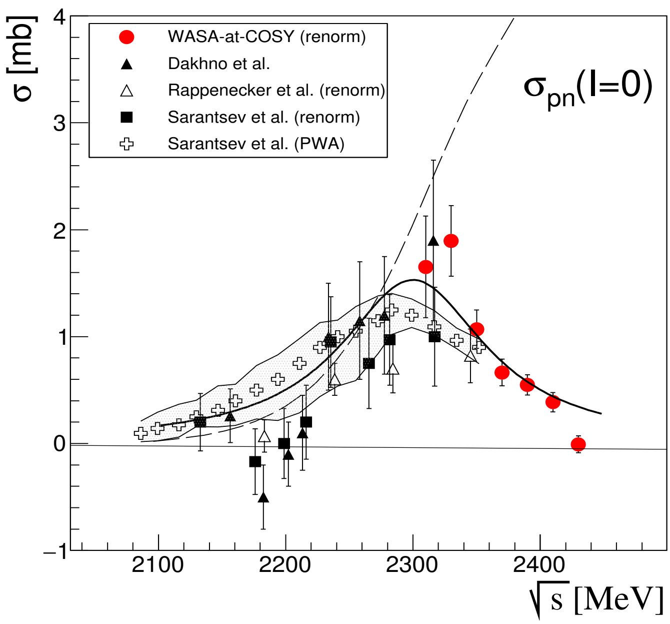

Fig. 2. The pn-induced isoscalar single-pion production total cross section in dependence of the total c.m. energy $\sqrt{s}$. Shown are the results from WASA-at-COSY [12] and Refs. [15, 16, 20, 21] as well as the results of the partial-wave analyses of Ref. [22] (open crosses surrounded by a hatched band, which indicates the uncertainties). The solid line represents a Breit–Wigner with $m = 2310$ MeV and $\Gamma = 150$ MeV. The dashed line gives the expected energy dependence of a t-channel Roper excitation [12] adjusted arbitrarily in height to the data point at $\sqrt{s} = 2260$ MeV. From Ref. [13].

The resonance-like structure in the region of the Roper excitation points to the formation of an $N^*(1440)N$ dibaryonic system. To investigate whether this is indeed connected with the excitation of the Roper resonance, we plot in Fig. 3 the isoscalar $N\pi$ invariant mass distribution $M_{N\pi}(I=0)$ obtained from the WASA measurement. As we can see, there is a pronounced bump above practically no background in the region of the Roper resonance, which again can be well represented by a Breit–Wigner with $m = 1370$ MeV and $\Gamma = 150$ MeV.

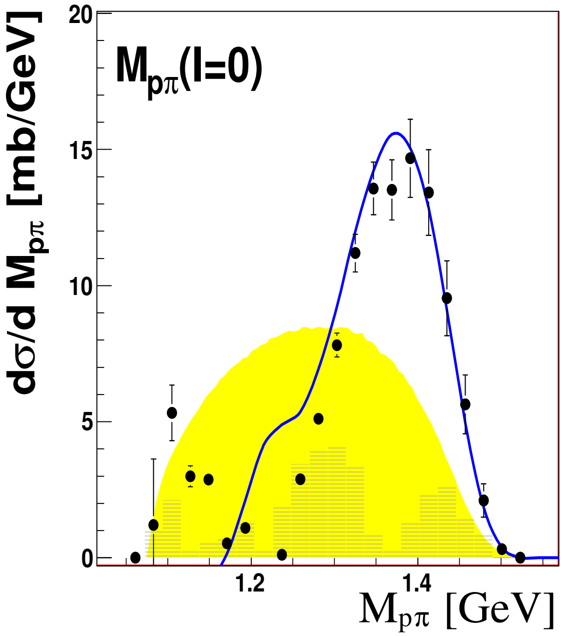

Fig. 3. The isoscalar $N\pi$ invariant mass distribution $M_{N\pi}(I=0)$ as obtained from the WASA measurements of the $pp \to pp\pi^0$ and $pn \to pp\pi^-$ reactions. The yellow area represents a pure phase-space distribution, the solid line gives a t-channel calculation for the Roper excitation with $m = 1370$ MeV and $\Gamma = 150$ MeV. From Ref. [12].

Adding the mass of a nucleon to the Roper mass extracted from Fig. 3, we end up with 2310 MeV, which is just the mass of the bump structure seen in the isoscalar total cross section. If we relate the effective Roper mass seen here to its pole position, then we observe the $N^*(1440)N$ system just at threshold. If we relate the effective Roper mass seen here with its nominal Breit–Wigner mass of 1440 MeV, then the Roper appears to be bound by about 70 MeV in the $N^*(1440)N$ system, and its observed reduced width can be well understood by the momentum dependence of its p-wave decay.

The width of the Roper resonance observed in the isoscalar $N\pi$ invariant mass spectrum equals that obtained for the bump structure in the isoscalar total cross section. This is actually not very surprising. As we know, *e.g.*, from tetra- and pentaquark studies [2], due to the tiny available phase space near threshold, the decay width of near-threshold states is tiny, if the decay products are hadronically stable. In our case, the decay products of the $N^*(1440)N$ dibaryonic system are N and $N^*(1440)$, and the latter is not hadronically stable and has a large width. Hence, we see just the width of the Roper resonance in the dibaryonic system.

Next, we have to consider the spin and parity of the $N^*(1440)N$ system. From the partial-wave analyses of Sarantsev *et al.* [22], we know that there are two dominating isoscalar NN partial waves in the region of interest: the ${}^3S_1$–${}^3D_1$ pn partial wave, where N and $N^*(1440)$ are in relative S wave leading to $I(J^P) = 0(1^+)$ and the ${}^1P_1$ np partial wave, where N and $N^*(1440)$ are in relative P wave yielding $I(J^P) = 0(1^-)$. Note that 1^+ and 1^- are the only possible J^P combinations for isoscalar S and P waves in the NN system.

At first glance, it might not appear very convincing that just two resonances sit practically on top of each other producing that way a single resonance-like structure in the total cross section. However, exactly such a scenario is observed also near the ΔN threshold, where the isovector $0^-, 2^+, 2^-$, and 3^- dibaryonic states happen to have similar masses and widths with differences small compared to their width [23–25]. For recent reviews about this issue, see, *e.g.*, Refs. [26, 27]. And since the width of the $N^*(1440)N$ states is still substantially larger than that of the ΔN states, small differences in mass and width are washed out in the summed up shape.

3. Isoscalar two-pion production in NN collisions

In addition to its single-pion decay, the Roper resonance decays also by two-pion emission, though it is not the dominating decay process. Hence, the isoscalar $N^*(1440)N$ system should also show up in isoscalar two-pion production, if the background situation is favorable. Indeed, there is such a situation in the $pn \to d\pi^0\pi^0$ reaction. The energy dependence of its total cross section measured by WASA [28, 29] is shown in Fig. 4.

The most dominating feature there is, of course, the excitation of the $d^*(2380)$ dibaryon resonance. The solid curve gives a description of this resonance with a momentum-dependent width [30], which describes the data very well except in its low-energy tail. There, the resonance curve underpredicts the data substantially. Actually, this is just the location where we expect strength due to the two-pion decay of the $N^*(1440)N$ system. If we subtract the curve from the data in this region, then we obtain some bell-shaped distribution around $\sqrt{s} \approx 2.3$ GeV (black dots), the high-energy side of which is, of course, highly dependent on the $d^*(2380)$ description. It is intriguing to associate this bump with the two-pion decay of the $N^*(1440)N$

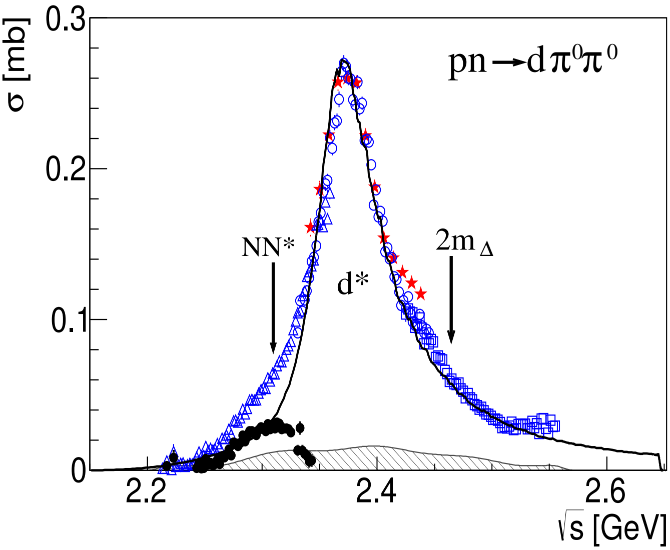

Fig. 4. The energy dependence of the total cross section of the $pn \to d\pi^0\pi^0$ reaction measured by WASA-at-COSY [28, 29] (blue and red symbols). The hatched area represents an estimate of systematic uncertainties. The solid curve gives a calculation of the $d^*(2380)$ dibaryon resonance with momentum-dependent widths [30] including both the Roper and $\Delta\Delta$ t-channel excitations as background reactions. The black solid dots represent the difference between this calculation and the data at low energies. From Ref. [12].

systems. Having here a peak cross section of about 30 μb, we may estimate the contributions from the other two-pion production channels with isoscalar contributions by isospin rules and end up finally with a total of roughly 150 μb [13].

We note in passing that the two-pion production via the $N^*(1440)N$ systems can also be described successfully as sequential single-pion processes by accounting for the two-pion decay of the Roper resonance. Using the formalism of Oset *et al.* [31] for sequential single-pion production, we arrive at the proper value for the observed cross section [32].

4. Branching ratios of the $N^*(1440)N$ dibaryonic systems

Having identified all inelastic decay channels, we may extract the branching ratios for the $N^*(1440)N \to NN, NN\pi$, and $NN\pi\pi$ transitions in analogy to what was done for $d^*(2380)$ [33]. From the partial-wave analyses of Ref. [22], we infer that about 25% of the peak cross section in isoscalar single-pion production is due to the $I(J^P) = 0(1^+)$ state and 75% due to the $I(J^P) = 0(1^-)$ state. By using unitarity, we arrive at elastic branchings of 0.04 and 0.15, respectively. Similarly, the branching into the $NN\pi$ and $NN\pi\pi$ channels are roughly 0.8 and 0.2, respectively [13]. This means that these resonances reside predominantly in the inelastic channels, in particular in the $NN\pi$ channel. Its tiny elasticities make it very hard to sense them in elastic scattering.

5. Isovector two-pion production in NN collisions

Since the Δ resonance decays only by single-pion emission, even the isovector two-pion production is free of single-Δ contributions. Only above $\sqrt{s} = 2.3$ GeV, Δ degrees of freedom enter by the $\Delta\Delta$ excitation process. Hence, at lower energies, the Roper excitation constitutes the only resonance reaction. The situation is particularly attractive in the $pp \to pp\pi^0\pi^0$ channel due to its reduced isospin combinations in its subsystems [34]. Exclusive and kinematically complete measurements have been carried out by PROMICE/WASA and CELSIUS/WASA in this particular region. From the different invariant-mass and opening angle spectra, the decay routes $N^*(1440) \to \Delta\pi \to N\pi\pi$ and $N^*(1440) \to N\sigma$ could be well separated, and their relative branching determined. In contrast to previous listings [35], we find a ratio of 1.0 (1) for these two branchings in good agreement with more recent evaluations [2].

In Fig. 5, we show the measured energy dependence of the total cross section. After a steep rise at threshold, the cross section levels off near $\sqrt{s} = 2.3$ GeV before it starts rising again beyond $\sqrt{s} = 2.4$ GeV. Whereas the first rise is due to Roper excitation, the second rise is associated with the $\Delta\Delta$ excitation. If we make an isospin decomposition of all two-pion production channels with regard to these excitation processes, then we get an energy dependence for N^* excitations, which is given by asterisk symbols in Fig. 5 [36]. This distribution shows again a bump-like structure peaking around 2.3 GeV and a width of 140 MeV. This suggests that also here we deal possibly with an $N^*(1440)N$ system, but now with $I(J^P) = 1(0^+)$ connected with the $^1S_0$ NN partial wave in the initial pp system.

6. Influence of the $N^*(1440)N$ dibaryonic systems on the NN interaction

Dibaryons constitute hexaquark configurations and hence are a link between meson–nucleon and quark degrees of freedom in the interaction of two nucleons. These considerations have been taken into account in the dibaryon NN interaction model of Kukulin, Platonova *et al.* [41, 42] based on ideas developed in Refs. [43, 44]. In this model, the intermediate- and short-range

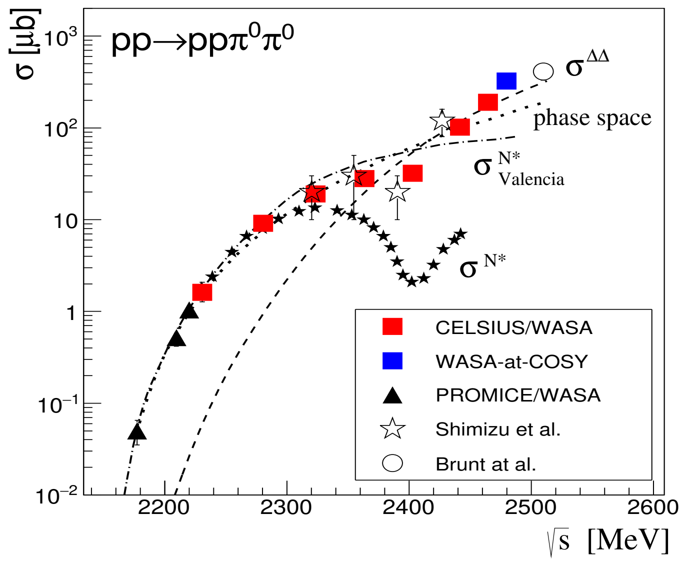

Fig. 5. The energy dependence of the total cross section of the $pp \rightarrow pp\pi^0\pi^0$ reaction measured by PROMICE/WASA [37], CELSIUS/WASA [36], WASA-at-COSY [38], and earlier measurements [17, 39]. The dotted, dash-dotted, and dashed lines give the expected energy dependence for pure phase space as well as t-channel Roper and $\Delta\Delta$ excitations, respectively [40]. The filled stars display the result of an isospin analysis of all two-pion production channels regarding N^* excitations [36]. From Ref. [42].

part of the NN interaction, which covers the region where the nucleons overlap, is described by s-channel exchange of intermediate dibaryons representing six-quark configurations. That way, it replaces the t-channel exchange of a multitude of heavy mesons in conventional models. The only meson exchange kept in this model is the one-pion exchange for the long-range part of the interaction, where the two nucleons practically no longer overlap. The beauty of this model is that it works even above the pion emission threshold, since the intermediate dibaryons get then on mass shell and decay by meson emission. That way, this model automatically includes inelastic scattering and hence works up to the GeV range. In addition and most importantly, the intermediate dibaryons needed in this model for the description of the low angular momentum partial waves can be cross-checked experimentally by searching for them in meson-production measurements.

In Ref. [41], it is demonstrated that this model can describe very successfully the experimental phase shifts [45, 46] both in the real and in the imaginary parts up to the GeV range for S, P, D, and F waves. The dibaryons extracted in their model turn out to be in very good agreement with the experimental findings. In Ref. [42], it is shown that the looping of the $N^*(1440)N$ configurations with $I(J^P) = 1(0^+)$ and $0(1^+)$ in the Argand diagrams of the $^1S_0$ and $^3S_1$ partial wave is very small due to their tiny elasticities and hence it is hard to identify them uniquely in partial-wave analyses. Nevertheless, as demonstrated in Ref. [42], the influence of $N^*(1440)N$ resonances on the phase shifts turns out to be crucial over the full energy range — in particular for the S waves (Fig. 6), where the overlap of the two nucleons is at maximum.

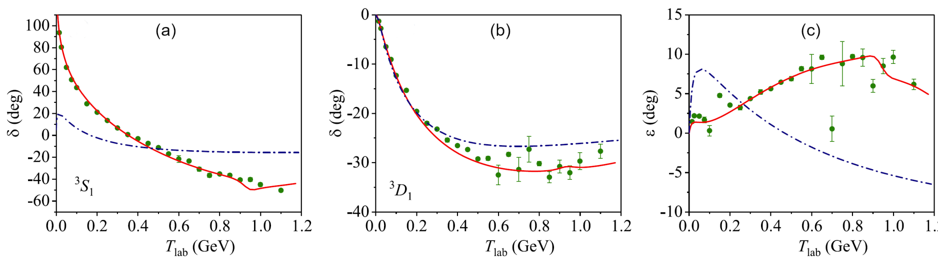

Fig. 6. Phase shifts δ for the coupled NN partial waves $^3S_1$ (a) and $^3D_1$ (b) as well as the mixing angle ϵ. The solid dots display the single-energy solutions of the SAID partial-wave analyses [45], the solid curves show the results of the dibaryon NN interaction, and the dash-dotted lines represent the results of the pure one-pion exchange. From Ref. [42].

7. Conclusions

Even 60 years after its discovery by L.D. Roper, the $N^*(1440)$ resonance is still a matter of utmost attraction both theoretically and experimentally. The fact that its pole values differ strongly from its Breit–Wigner mass and width increases its complexity and has caused, in the past, quite some confusion. In NN collisions, the Roper excitation usually appears as a bump above a substantial background and seems to have lower values for its mass and width as compared to what is observed in $N\pi$ and $N\gamma$ studies.

In exclusive and kinematically complete (with overconstraints) measurements at CELSIUS/WASA and WASA-at-COSY, the Roper resonance has been observed free of background in single- and double-pion production, where it exhibits a resonance-like energy dependence in total cross sections. This is shown as being due to the formation of $N^*(1440)N$ dibaryonic systems, where the Roper resonance is bound by roughly 70 MeV. This binding explains also its reduced width of 150 MeV observed in the invariant mass spectrum $M_{N\pi}(I = 0)$.

That way, the puzzling discrepancy between $N\pi$ and $N\gamma$ results for the Roper resonance and those obtained by NN collisions is resolved by the finding that in the latter case, the Roper resonance merges into an $N^*(1440)N$ configuration.

The observation of $N^*(1440)N$ dibaryons is very important for the understanding of the NN interaction, where they turn out to be crucial for the understanding of the NN partial waves, in particular the S and P waves, where the colliding nucleons strongly overlap and hence reveal their quark degrees of freedom.

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