Evidence for a ’Narrow’ Roper Resonance -
The Breathing Mode of the Nucleon

H. Clement\textsuperscript{1}, T. Skorodko\textsuperscript{1}, M. Bashkanov\textsuperscript{1}, D. Bogoslawsky\textsuperscript{2}, H. Calén\textsuperscript{3}, F. Cappellaro\textsuperscript{4}, L. Demiroers\textsuperscript{5}, E. Doroshkevich\textsuperscript{1}, C. Ekström\textsuperscript{3}, K. Fransson\textsuperscript{3}, L. Gustafsson\textsuperscript{4}, B. Höistad\textsuperscript{4}, G. Ivanov\textsuperscript{2}, M. Jacewicz\textsuperscript{4}, E. Jiganov\textsuperscript{2}, T. Johansson\textsuperscript{4}, M. Kaskulov\textsuperscript{1}, O. Khakimova\textsuperscript{1}, S. Keleta\textsuperscript{4}, I. Koch\textsuperscript{4}, F. Kren\textsuperscript{1}, S. Kullander\textsuperscript{4}, A. Kupś\textsuperscript{3}, A. Kuznetsov\textsuperscript{2}, P. Marciniewski\textsuperscript{3}, B. Martemyanov\textsuperscript{11}, R. Meier\textsuperscript{1}, B. Morosov\textsuperscript{2}, W. Oelert\textsuperscript{8}, C. Pauly\textsuperscript{5}, H. Pettersson\textsuperscript{4}, Y. Petukhov\textsuperscript{2}, A. Povtorejko\textsuperscript{2}, R.J.M.Y. Ruber\textsuperscript{3}, K. Schöning\textsuperscript{4}, W. Scobel\textsuperscript{5}, B. Shwartz\textsuperscript{9}, V. Sopov\textsuperscript{11}, J. Stepaniak\textsuperscript{7}, P. Thörngren-Engblom\textsuperscript{4}, V. Tikhomirov\textsuperscript{2}, A. Turowiecki\textsuperscript{10}, G.J. Wagner\textsuperscript{1}, M. Wolke\textsuperscript{4}, A. Yamamoto\textsuperscript{6}, J. Zabierowski\textsuperscript{7}, J. Złomanczuk\textsuperscript{4}

\textsuperscript{1} Physikalisches Institut der Universität Tübingen, D-72076 Tübingen, Germany 
\textsuperscript{2} Joint Institute for Nuclear Research, Dubna, Russia 
\textsuperscript{3} The Svedberg Laboratory, Uppsala, Sweden 
\textsuperscript{4} Uppsala University, Uppsala, Sweden 
\textsuperscript{5} Hamburg University, Hamburg, Germany 
\textsuperscript{6} High Energy Accelerator Research Organization, Tsukuba, Japan 
\textsuperscript{7} Soltan Institute of Nuclear Studies, Warsaw and Lodz, Poland 
\textsuperscript{8} Forschungszentrum Jülich, Germany 
\textsuperscript{9} Budker Institute of Nuclear Physics, Novosibirsk, Russia 
\textsuperscript{10} Institute of Experimental Physics, Warsaw, Poland 
\textsuperscript{11} Institute of Theoretical and Experimental Physics, Moscow, Russia

(CELSIUS-WASA Collaboration)

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Abstract

All the time since its discovery the $N^*(1440)$ baryon state, commonly known as Roper resonance, has been a state with many question marks - despite of
its 4-star ranking in the particle data book. One reason is that it does not produce any explicit resonance-like structures in the observables of $\pi N$ or $\gamma N$ reactions. Only in partial wave analyses of $\pi N$ scattering data a clear resonance structure gets obvious in the $P_{11}$ partial wave. Very recent measurements of the $J/\Psi$ decay by the BES collaboration and of the $pp \rightarrow np\pi^+$ reaction at 1.3 GeV by the CELSIUS-WASA collaboration show for the first time a clear resonance structure in the invariant $n\pi^+$ mass spectrum for the Roper resonance at $M \approx 1360$ MeV with a width of about 150 MeV. These values agree very favorably with the pole position results of recent $\pi N$ phase shift analyses. In consequence of this very low-lying pole position, which is roughly 100 MeV below the nominal value, the decay properties have to be reinvestigated. From our two-pion production data we see that the decay mainly proceeds via $N^* \rightarrow N\sigma$, i.e. a monopole transition as expected for the breathing mode of the nucleon.

1 Introduction

Some 40 years ago, when David Roper undertook one of the first energy-dependent phase shift analyses of $\pi N$ scattering data, he discovered a resonance in the $P_{11}$ partial wave by noting that this particular phase shift proceeds from $0^\circ$ to $140^\circ$ in the investigated energy range in much the same way as the $P_{33}$ and $D_{13}$ phaseshifts do, where corresponding resonances were already established. By looking on the energy, where the $P_{11}$ phase shift passes through $90^\circ$ he arrived at a mass of 1485 MeV for this new resonance - which later on was named after him. The peculiarity of this resonance, however, has been all the time, that no sign of a resonance-like structure could ever be observed in experimental observables, in particular not in the total cross section, where a resonance should show up by its Breit-Wigner-like energy dependence. However, the Roper resonance obviously is excited in the $\pi N$ scattering process such weakly, that it is buried underneath a wealth of other processes and can be sensed only via a very detailed partial wave analysis - a feature, which had been noted already by Roper himself in his paper \cite{1}. There he had been pointing out that , whereas ”previous $\pi N$ resonances were discovered from observations on the qualitative behavior of experimental observables”, the Roper resonance ”is not associated with conspicuous features in the observables measured so far”.

This situation did not change much since then, though a huge number of very precise $\pi N$ and also $\gamma N$ reaction data have been obtained meanwhile.
However, what has changed is the precision of partial wave analyses and their methods to reveal resonances. In former times usually a Breit-Wigner shape was fitted directly to the partial wave amplitudes despite the fact that the latter in general still include background terms. Such fits provide the so-called Breit-Wigner (BW) mass and width parameters of a resonance - see PDG [2]. Nowadays more advanced techniques as speed plot [3] and pole search techniques [4, 5] in the complex plane of the partial wave are used to deduce the appropriate pole parameters, which should be free of background contributions to a much higher degree and hence should represent much more appropriately the physical relevant mass and width of a resonance. Whereas these two methods give similar results for many of the resonances, they strongly deviate - see PDG [2] - in case of the Roper resonance, which in $\pi N$ scattering sits upon a huge background of inelastic processes due to pion production. This large inelasticity associated with the Roper resonance signals already that this resonance most likely decays not into the (elastic) $\pi N$ channel but into $\pi\pi N$ channels.

All recent $\pi N$ partial wave analyses [3, 7, 4, 6] agree that in case of the Roper resonance the BW method mass and width parameters are in the range $M_{BW} = 1420 - 1470$ MeV and $\Gamma_{BW} = 200 - 450$ MeV, whereas the pole values are $M_{pole} = 1350 - 1380$ MeV and $\Gamma_{pole} = 160 - 220$ MeV [2] with the most recent SAID values being $M_{pole} = 1357$ MeV and $\Gamma_{pole} = 160$ MeV [6]. This means that in truth the Roper resonance lies much lower than believed earlier based on the BW method and that it is also much more narrow than believed earlier. Its widths is now no longer exceptionally large and fits to the typical width of nucleon excitations.

2 Previous Attempts to 'see' the Roper Resonance

Of course, there have been innumerable attempts to see the Roper directly in the data, i.e. by typical signs of a resonance in the observables. Shortly after its discovery by Roper a large number of inclusive single-arm measurements of pion-proton and proton-proton collisions in the GeV energy range were presented taken preferentially with magnetic spectrometers. By varying the scattering angles the four-momentum transfer relevant for the obtained missing mass spectra was varied accordingly. As a result such spectra displayed a bump structure around a missing mass of 1440 MeV as long as the four momentum transfer was very small [8, 9, 10]. For larger transfer momenta this structure disappeared. Whereas some people argued to have visible evidence
for the Roper excitation, others showed that kinematical reflections in sense of the Deck model [11] could be a likely explanation for the observed bumps, too - in particular, since these reflections should mainly appear at small momentum transfers. Indeed, it was demonstrated by an exclusive two-pion production measurement of pp collisions at 6.6 GeV/c that a bump between 1400 and 1500 MeV appears in the invariant $M_{p\pi^+\pi^-}$ spectrum, if the other proton simultaneously is excited to $\Delta^{++}$ in a peripheral collision process. I.e., the bump occurs, if the $\pi^+$ is erroneously associated with the wrong proton - as is the case, when constructing missing mass spectra from inclusive measurements and thus creating the phenomenon of kinematic reflections. Hence this problem is unavoidable in inclusive measurements.

This topic, however, came back very recently, when Morsch and Zupranski [12] reinvestigated the old inclusive measurements. They demonstrated that the many of these inclusive spectra not only could be fitted very reasonably with resonance parameters of $M \approx 1400$ MeV and $\Gamma \approx 200$ MeV - i.e. parameters, which agree quite well to their results from $\alpha$ scattering, see below - but, more essentially, that also the strong momentum transfer dependence of the observed bumps in the inclusive spectra could be associated with the characteristics of a monopole transfer form factor.

3 New Generation of Experiments, which ’see’ the Roper Resonance

Since no possibility is known up-to-date to isolate the Roper resonance in experimental observables of pion- and photon-induced reactions, attempts have been undertaken to look for its signature in other reactions, which could filter out the Roper excitation in a somewhat better manner. Since the Roper resonance has quantum numbers identical to those of the nucleon, it would be easiest to excite it by a scalar-isoscalar probe. However, the only basic hadronic probe of such characteristics is the $\sigma$ meson, which unfortunately decays immediately into two pions, i.e. can not be used as a incident beam particle. Hence it has been proposed to use a $\alpha$ particle beam instead - so to speak as a next best choice, which is handable experimentally. Indeed, Morsch et al. [13] succeeded to see the Roper resonance in the missing mass spectrum of inelastic $\alpha$ scattering off hydrogen sitting upon background stemming from $\Delta$ excitation in the $\alpha$ particle. Assuming a smooth background underneath the Roper peak they extracted a mass of 1390 MeV and a width of 190 MeV, i.e. close to the pole parameters. However, as pointed out by the
Valencia group [14] the $\Delta$ excitation process in the $\alpha$ particle may interfere with the Roper excitation process in the hit proton. Taking into account such an interference term the observed bump in the missing mass spectrum, unfortunately, can as well be described by the conventional BW-parameters.

Very recently the BES collaboration came up with the idea to look for $N^*$ excitations in $J/\psi$ decays. The new aspect is that since $J/\psi$ is isoscalar, the resulting $\bar{N}N^*$ and $N^*N$ systems also have to be isoscalar with the consequence that only $I = 1/2$ nucleon excitations are allowed in this decay. Besides a number of known higher-lying resonances also a small, but clear peak is observed at $M = 1358(6, 16)$ MeV with $\Gamma = 179(26, 50)$ MeV. Since these values agree very well with the SAID pole position parameters for the Roper resonance they associate this peak with the latter [15].

Last but not least there is the possibility of exciting the Roper resonance simply by nucleon-nucleon collisions at low energies - a point, which never has been checked properly by exclusive pion-production reactions. As we have shown [16, 17] in corresponding $\pi\pi$-production experiments close to threshold, the inelastic collision process is governed by $\sigma$ exchange, i.e. the Roper excitation this way may take place with virtual $\sigma$ particles as an ideal excitation probe. Besides it turns out that even in case of pion exchange the Roper excitation is strongly favored in the $pp \rightarrow np\pi^+$ channel by isospin couplings. Whereas $\Delta^{++}$ excitation is expected to be the dominant structure seen in the $M_{p\pi^+}$ spectrum, the Roper excitation should be the leading structure in the $M_{n\pi^+}$ spectrum, since there the $\Delta^+$ excitation is suppressed by an order of magnitude. In addition, if the reaction is carried out at sufficiently low energies, such that only the lowest-lying $\Delta$ and $N^*$ resonances can be excited, no kinematic reflections from higher lying resonances can contribute. Also the formfactors of $\Delta$ and Roper should still be large enough, in order not to suppress these excitations.

4 Exclusive Measurements at CELSIUS-WASA

In order to shed more light on this issue exclusive measurements of the reactions $pp \rightarrow N\pi$ and $pp \rightarrow NN\pi\pi$ have been carried out at several energies from 650 - 1450 MeV at the CELSIUS storage ring using the $4\pi$ WASA detector setup [18] including the pellet target system, see Fig.1.

For the reactions under consideration forward going protons have been detected in the forward detector and identified by the $\Delta E$-E technique using corresponding informations from quirl and range hodoscope, respectively.
Figure 1: Side view of the WASA detector: The SuperConducting Solenoid (SCS) and the iron yoke for the return path of magnetic flux is shown shaded. Plastic scintillators are situated in the Plastic Scintillator Barrel (PSB), Forward Window Counters (FWC), Forward Trigger Hodoscope (FTH), Forward Range Hodoscope (FRH), Forward Range Intermediate Hodoscope (FRI), Forward Veto Hodoscope (FVH) and Backward Veto Counters (BVC). Cesium Iodide scintillators are situated in the Scintillator Electromagnetic Calorimeter (SEC). Proportional wire drift tubes, straws, make up the Mini Drift Chamber (MDC) and the Forward Proportional Chambers (FPC).

Charged pions, protons as well as gammas (from $\pi^0$ decay) have been detected in the central detector. This way the full four-momenta have been measured for all charged and $\pi^0$ particles of an event allowing thus kinematic fits with overconstraints. In addition the direction of neutrons could be measured in most cases by their hit pattern in forward and central detectors.

The $np\pi^+$ channel has been analyzed so far at $T_p = 1100$ and 1300 MeV. Whereas the lower energy just suffices to reach the Roper excitation up to its pole position, the higher energy allows to see the Roper excitation beyond its pole. Fig. 2 shows as an example the $M_{p\pi^+}$ and $M_{n\pi^+}$ spectra taken at 1300 MeV. In the first one, which is purely $I = 3/2$, the $\Delta^{++}$ resonance is the striking feature with no other significant signals of further resonances. A simple BW ansatz for the $\Delta^{++}$ resonance gives a nearly perfect description for this spectrum without any need for any additional background terms. For the $M_{n\pi^+}$ spectrum this ansatz predicts a distribution close to phase space. Experimentally we observe, however, a large resonance-like structure peaking near 1350 MeV, which we associate with the Roper excitation. The dashed lines in Fig.2 show a calculation assuming BW shapes for both the $\Delta^{++}$ and the Roper excitation, the latter with $M = 1350$ MeV and $\Gamma = 140$ MeV.
Figure 2: Invariant mass spectra $M_{p\pi^+}$ and $M_{n\pi^+}$ obtained from the measurement of the $pp \to np\pi^+$ reaction at $T_p = 1300$ MeV. The shaded areas show the pure phase space distributions, whereas the dashed lines show calculations assuming BW shapes for both the $\Delta^{++}$ and the Roper excitation [19].

No background is needed for the description of the data, which means that the obtained resonance values for the Roper may be associated with its pole parameters.

We see that the obtained values are in excellent agreement with SAID and BES pole parameters for the Roper resonance. For the first time such a clear Roper excitation has been observed, its signal in the $M_{n\pi^+}$ spectrum appears to be qualitatively as strong as that of the $\Delta^{++}$ in the $M_{p\pi^+}$ spectrum.

5 Decay Properties of the Roper Resonance

The decay properties of the Roper resonance as given in PDG are not only very vague, they also have been deduced not for the pole position of the Roper resonance, but rather for its BW mass [6, 4]. The latter - as already discussed above - is much larger than the pole value, which represents the proper resonance mass and hence is relevant for the quotation of branching ratios, which are defined at $\sqrt{S} = M_{pole}$. Since the now established pole mass of $M_{pole} \approx 1350$ MeV is as much as 100 MeV below the BW mass, this has enormous consequences for the branching ratios. By lowering the mass of a resonance the phase space of the decay channels gets reduced accordingly. Such a reduction is especially severe for decay channels, which involve finite angular momenta between the decay products, since in such cases the decay
width depends on high powers of the available decay momenta of the emitted particles. In case of the Roper decays this concerns in particular the decay $N^* \rightarrow N\pi$, which proceeds with a p-wave between nucleon and pion, and still much more severely the decay $N^* \rightarrow \Delta \pi \rightarrow N\pi\pi$, which proceeds with double p-wave between the two pions and the nucleon. In addition, the new values for the pole mass of the Roper just coincide with the $\Delta\pi$ branch cut, i.e. with the sum of $\Delta$ and pion masses. This means that aside from the effect of the finite width of the $\Delta$ there is essentially no phase space left any longer for the Roper decay into this channel.

The branching ratio for the single-pion decay of the Roper can be derived directly from the energy dependence of the imaginary part of the $P_{11}$ partial wave amplitude [20]. Using $M_{\text{pole}} = 1350$ MeV we arrive at about 0.3 for this branching value (compared to 0.55 - 0.75 given in PDG), i.e. this decay can no longer be considered as the main decay branch of the Roper decay.

The decay of the Roper resonance into nucleon and two pions can be studied best by two-pion production in NN-collisions. There the Roper excitation constitutes the lowest resonance, which can contribute to this reaction. As
a consequence the near-threshold region of this reaction is ideally suited for
the investigation of the Roper decay into two pions and nucleon \([21, 16, 17]\).
In addition, both decays \(N^* \to N\sigma \to N\pi\pi\) and \(N^* \to \Delta\pi \to N\pi\pi\) not only
contribute to the cross section of two-pion production, they even contribute
interfering in the \(\pi^+\pi^-\) and \(\pi^0\pi^0\) channels, since there they can end up in
identical final states. From the study of their interference patterns in the
differential cross sections, in particular in the \(M_{\pi\pi}\) spectra, we have deduced
the relative ratio of both decay branches in exclusive near-to-threshold mea-
surements at \(T_p = 750\) and 775 MeV \([17]\). At the BW- mass this ratio gives
a value of 3.4(3) for the branching of the decay \(N^* \to \Delta\pi \to N\pi\pi\) relative
to \(N^* \to N\sigma \to N\pi\pi\). This value is in accordance with the PDG value of
4(2), though much more precise. However, if we look at this ratio not at the
BW-mass, but on the much more appropriate pole mass of the Roper, then
we arrive at values of 1.0\((1)\), if we use \(M_{\text{pole}} = 1372\) MeV - an earlier value -
or 0.6\((1)\), if we use our present value of \(M_{\text{pole}} = 1350\) MeV. These numbers
just illustrate the huge dependence of this ratio on the pole mass. This huge
dependence is - as discussed above - due to the change in the branching of
the decay via the \(\Delta\) resonance, both due to phase space shrinkage and in
particular due to the involvement of double p-waves. The results also show
that at the proper Roper mass the dominant two-pion decay channel is no
longer the one via the \(\Delta\), but rather the one via the \(\sigma\) channel.

The \(pp\pi^+\pi^-\) channel, where the above values for the relative ratio have
been obtained, may contain both isoscalar and isovector \(\pi\pi\) contributions.
In order to isolate the isoscalar part we have to go to the \(\pi^0\pi^0\) channel,
which is free of any isovector contributions due to Bose symmetry. Fig. 3
shows our (preliminary) results for this channel at \(T_p = 775\) Mev and at \(T_p = 900\) MeV. Note that the Roper resonance already gets excited kinematically
up to its pole mass at \(T_p = 900\) MeV. The shift of the data in the \(M_{\pi\pi}\)
spectrum relative to the distribution for pure phase space originates from the
interference between \(N^* \to N\sigma \to N\pi\pi\) and \(N^* \to \Delta\pi \to N\pi\pi\) routes as
demonstrated in Refs. \([16, 17]\). We see that in the \(\pi^0\pi^0\) channel the shift and
hence the contribution from the decay via the \(\Delta\) resonance is much smaller
(solid lines in Fig. 3) than expected from the analysis of the \(\pi^+\pi^-\) data
(dashed lines in Fig. 3). As a consequence we obtain from the analysis of
\(\pi^0\pi^0\) channel data a value for the relative branching as low as 0.1.

From this we arrive at the following results for the branching ratios of the
Roper decay: Since the single-pion decay gives only a branching of about 0.3,
the branching into both two-pion decay channels must be roughly 0.7. Since
furtheron the branching between \(N^* \to \Delta\pi \to N\pi\pi\) and \(N^* \to N\sigma \to N\pi\pi\)
channels is only 0.1 for the isoscalar part, this then means that the \( N\sigma \) decay channel is the by far largest one of all Roper decays. From this result we see that the Roper resonance with its pole at 1350 MeV indeed constitutes the breathing mode of the nucleon.

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