Decay Properties of the Roper Resonance from $pp \rightarrow pp\pi^+\pi^-$

H. Clement representing the PROMICE/WASA collaboration

Physikalisches Institut der Universität Tübingen, Morgenstelle 14, D-72076 Tübingen

Received: date / Revised version: date

Abstract. Exclusive measurements of the two-pion production channel $pp \rightarrow pp\pi^+\pi^-$ have been carried out near threshold at CELSIUS with the PROMICE/WASA detector. They reveal $pp \rightarrow pp^*(1440) \rightarrow pp\sigma \rightarrow pp(\pi^+\pi^-)$ as the dominant process at these energies, however, the data exhibit also significant contributions from $p^*(1440) \rightarrow \Delta\pi \rightarrow p(\pi^+\pi^-)$. From the observed interference of these routes their relative branching ratio is derived.

PACS. 13.75.-n hadron induced low- and intermediate-energy reactions – 14.20.Gk baryon resonances with $S=0$ – 25.40.Ve nucleon-induced reactions above meson production thresholds

1 Introduction

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. 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 find the Roper excitation to rest solely on meson-nucleon dynamics, whereas another recent investigation proposes it to be actually two resonances with one being the breathing mode and the other one a $\Delta$ 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 $N^* \rightarrow N(\pi\pi)_{I=1=0} = N\sigma$, i.e., the decay into the $\sigma$ channel. A competitive and according to present knowledge actually much stronger decay channel is the Roper decay into the $\Delta(1232)$ resonance $N^* \rightarrow \Delta\pi$. However, this decay channel is not very well defined, since the $\Delta$ 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 $N^* \rightarrow N\sigma$ decay.

Calculations of the Valencia group predict the $pp \rightarrow pp\pi^+\pi^-$ reaction at energies not far above threshold to
proceed dominantly via $\sigma$ 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 $T_p = 750$ MeV support very much this conception. This finding suggests $pp \rightarrow pp\pi\pi$ to be unique in the sense that it selectively provides the excitation mode “$\sigma$” $N \rightarrow N^*$ (where “$\sigma$” stands now for the $\sigma$ exchange), which is not accessible in any other basic reaction process leading to the Roper excitation.

2 Data and Analysis

In Fig. 1 we present a selection of the 750 MeV data together with new data at $T_p = 775$ MeV, again taken with the PROMICE/WASA detector setup at CELSIUS. For experimental details see [6,7,8]. 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. 1) and compatible with the low-en 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

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

which in the full reaction amplitudes complements the propagators for $\sigma$ 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 $D_{\Delta^0}$ are the $\Delta$ propagators, the constant 1 stands for the process $N^* \rightarrow N\sigma$ and the second term for the decay route $N^* \rightarrow \Delta\pi \rightarrow N\sigma$, where $k_1$ and $k_2$ 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 $\delta_{\pi^+\pi^-} = \delta(k_1, k_2)$ is the opening angle between the two pions, see Fig. 1. 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 $a = c < k_1 k_2 (3D_{\Delta^{++}} + D_{\Delta^0})$, 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. 1, bottom).

In order to illustrate the sensitivity of the data to the mixing of both routes we show calculations for pure phase space, pure transitions $N^* \rightarrow N\sigma$ and $N^* \rightarrow \Delta\pi \rightarrow N\sigma$ 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.

3 Results

From a fit to the data the coefficient $c$ can be determined and thus also the ratio $R(M_{N\pi\pi})$ of the partial decay widths for the routes $N^* \rightarrow \Delta\pi \rightarrow N\pi\pi$ and $N^* \rightarrow N\sigma$ in dependence of the average $N\pi\pi$ mass populated in the reaction. For $T_p = 750$ MeV we have $< M_{N\pi\pi} > = 1264$ MeV and for $T_p = 775$ MeV $< M_{N\pi\pi} > = 1272$ MeV. Having determined $c$ from the data we obtain $R(1264) = 0.040(4)$ and $R(1272) = 0.060(6)$. This result just reflects the fact, that in this very low-en energetic tail of the Roper
Fig. 1. 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 $pp \rightarrow pp\pi^+\pi^-$ at $T_p = 750$ MeV (left) and $T_p = 775$ MeV (right). Pure phase space calculations are shown by the shaded area, dotted lines show the case of a pure $N^* \rightarrow N\sigma$ decay, whereas the dash-dotted lines exhibit the scenario for a pure $N^* \rightarrow \Delta\pi \rightarrow N(\pi^+\pi^-)_{I=\ell=0}$ decay. Solid and dashed curves finally show calculations assuming interference from both decay routes with $a = -0.20, -0.25$ and $-0.33$.

the $N^* \rightarrow N\sigma$ decay is by far the dominant route. However, due to its $k_1 \cdot k_2$ dependence the $N^* \rightarrow \Delta\pi$ route is rapidly growing, and finally will take over at higher energies. If we assume ansatz (1) to be valid also at higher energies, then we may extrapolate to the nominal Breit-Wigner resonance pole. The resulting value, $R(1440) = 3.9(3)$, compares very favorably with the PDG value of $4(2)$. Statistically our value is much more precise, however, it is still an extrapolation and depends on the validity of ansatz (1) also at higher energies and hence can not be considered model-independent. However, as we have demonstrated, the $pp \rightarrow pp\pi^+\pi^-$ reaction offers the possibility 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 $N^* \rightarrow N\pi\pi$ decay by successive increase of the incident proton energy — a program which is currently pursued at CELSIUS-WASA and COSY-TOF.

This work has been supported by DFG (Europ. Graduiertenkolleg 683) and BMBF (06 TU 987).

References

1. Particle Data Group, Eur. Phys. J. C15 (2000) 1
2. O. Krehl et al., Phys. Rev. C62 (2000) 025207
3. E. Hernández, E. Oset and M.J. Vicente Vacas, nucl-th/0209009
4. H.P. Morsch, P. Zupranski, Phys. Rev. C61(1999) 024002
5. L. Alvarez-Ruso, E. Oset, E. Hernández, Nucl. Phys. A633 (1998) 519 and priv. comm.
6. W. Brodowski et al., Phys. Rev. Lett. 88(2002) 192301
7. J. Pätzold, doctoral thesis, Universität Tübingen 2002 and to be submitted for publication
8. H. Calen et al., Nucl. Instr. Meth. A379 (1996) 57