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Higher baryon resonances in carbon-carbon collisions at 4.2 GeV/c per nucleon

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Abstract. The production of the $N(1440)$, the so-called Roper, and $N(1520)$ resonances in high-energy collisions of carbon nuclei with the carbon nucleus, using a 2 m propane bubble chamber, was investigated. Attention was paid to the two-pion decay mode of the higher baryon resonances. From the invariant masses of three-particle states ($p\pi^+\pi^-$) the mass and width of the resonances were obtained. The ratio of the resonances decay to ($\Delta\pi$) and ($N\pi\pi$) states was estimated.

PACS. 25.70.Ef Resonances – 14.20.Gk Baryon resonances with $S = 0$

1 Introduction

The study of baryon resonances is still an attractive subject for both theorists and experimentalists. Many resonances between $\Delta(1232)$ and mass of 2000 MeV/c^2 have been investigated. However, experimental results about the lowest nucleon excitation $N(1440$ MeV/$c^2)$, $(1/2^+)$, the so-called Roper ($N(1440)$) resonance, originate mainly from hadron-hadron collisions, while the data from nucleus-nucleus collisions are quite scarce. The data suggests that the Roper resonance mass lies in a quite wide interval and that the width is very large compared to nucleon resonances with masses higher than 1500 MeV/c^2 [1].

If we assume independent nucleon-nucleon interactions in the nucleus-nucleus collision, the Roper resonance is predominantly created in the reaction $NN \to N(1440)N$ with two dominant decay modes:

$$N(1440) \to N\pi \tag{1}$$

and

$$N(1440) \to N\pi\pi\,. \tag{2}$$

In the present analysis, we study the two-pion decay mode of the Roper resonance with branching ratio of 30–40%, as well as the $N(1440) \to \Delta\pi$ decay mode with the (total) branching ratio of 20–30% [1]. The situation with the $N(1520)$-resonance is practically the same. Several earlier papers [2–5] suggest that the width and mass of any baryon resonances, produced in high-energy nucleon collisions and in nucleus-nucleus collisions, could be different. For example, in ref. [5], results from $\alpha + N$ scattering are $M = (1420\pm30)$ MeV/c^2, $\Gamma = (300\pm40)$ MeV/c^2, and $M = (1370\pm20)$ MeV/c^2, $\Gamma = (190\pm20)$ MeV/c^2, and the authors tried to explain this fact by two different structures of the Roper resonance. In our previous works [6,7], we analyzed the $\Delta(1232)$ production in C + C collisions at 4.2 GeV/c per nucleon. This study did not confirm a Δ mass shift to lower values, but we found that the Delta width Γ is lower than that for free nucleon collisions. The main intention of this paper is to test these statements, studying the properties of Roper and higher baryon resonances produced in such collisions. The paper is organized as follows: The summary of the experimental procedures is described in sect. 2. Section 3 presents the results and discussion. Conclusions are given in sect. 4.

2 Experimental procedures

Using the data obtained at the 2 m propane bubble chamber exposed to a ^{12}C beam at Dubna Synthrophasotron we have studied the higher baryon resonances production. At incident momentum of 4.2 GeV/c per nucleon, 20594 C + C inelastic interactions were selected. Practically, all the secondaries have been detected in the chamber. To

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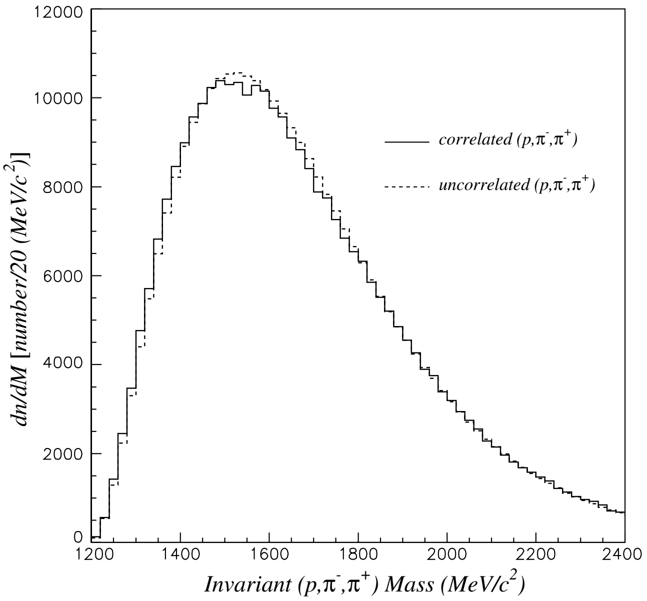

Fig. 1. The invariant-mass distribution for $(p\pi^+\pi^-)$ measured states in C + C collisions at 4.2 GeV/c per nucleon (solid line) and the background distribution (dashed line).

separate π^+ from the proton we are using momentum-range relations and the detection of the $\pi^+\mu^+e^+$ decay. The measured momenta of protons and pions were used to calculate the invariant mass of the $(p\pi^+\pi^-)$ system, M, from the relation

$$M^2 = (E_p + E_{\pi 1} + E_{\pi 2})^2 - (\vec{p}_p + \vec{p}_{\pi 1} + \vec{p}_{\pi 2})^2, \qquad (3)$$

where $E_p, E_{\pi 1}, E_{\pi 2}, \vec{p}_p, \vec{p}_{\pi 1}, \vec{p}_{\pi 2}$ are energy and momentum of the proton and pions, respectively.

The experimental invariant-mass distribution, $(\mathrm{d}n/\mathrm{d}M)$, for $(p\pi^+\pi^-)$ particles was produced by applying the following two criteria to every event:

1. The protons with momenta $p > 3$ GeV/c and angles between the beam and the direction of the emitted particle $\theta < 4°$ are treated as spectators and are excluded.

2. The protons emitted from the target carbon nucleus during the process of evaporation ($p < 300$ MeV/c) were eliminated.

To estimate the combinatorial background, we used the event mixing method. The procedure was as follows: We calculated the invariant mass for $(p\pi^+\pi^-)$ combinations randomly selecting each particle from different events and then the background distribution $(\mathrm{d}n^b/\mathrm{d}M)$ was normalized to the number of three-particle states in the spectrum. The invariant-mass distribution for $(p\pi^+\pi^-)$ measured states is shown in fig. 1 (solid line), as well as the background distribution (dashed line).

In order to select candidates for the Roper and other baryon resonances, we analyzed the distribution of the differences between invariant-mass spectra for correlated and uncorrelated events, defined by

$$D(M) = \left(\frac{\mathrm{d}n}{\mathrm{d}M}\right) - a\left(\frac{\mathrm{d}n^b}{\mathrm{d}M}\right), \qquad (4)$$

where a is the ratio between the number of non-resonance $(p\pi^+\pi^-)$ states and the total number of $(p\pi^+\pi^-)$ states. The factor a is simply connected to the resonance production rate (R). If the number of $(p\pi^+\pi^-)$ states which do originate from higher baryon resonances is denoted by n_R and the total number of $(p\pi^+\pi^-)$ states is denoted by n, then we have:

$$n_R = \int D(M)\mathrm{d}M = \int \left(\frac{\mathrm{d}n}{\mathrm{d}M}\right)\mathrm{d}M - a\int\left(\frac{\mathrm{d}n^b}{\mathrm{d}M}\right)\mathrm{d}M = n(1-a), \qquad (5)$$

and

$$R = \frac{n_R}{n} = 1 - a. \qquad (6)$$

Interpreting the distribution $D(M)$ as a pure baryon resonances signal, we have approximated it by a sum of three relativistic Breit-Wigner shapes [8]

$$b(M) = \sum_{i=1}^{3} \frac{I_i \Gamma_i M M_{Ri}}{(M^2 - M_{Ri}^2)^2 + \Gamma_i^2 M_{Ri}^2}, \qquad (7)$$

where M_{Ri}, Γ_i and I_i are the mass, the width and the relative intensity of the i-th resonance, respectively. The data set $D(M)$ for different values of the parameter a was fitted by the function $b(M)$ and χ^2 was found for each fit. The parameters M_{Ri}, Γ_i and I_i were determined by minimizing the difference $|D(M) - b(M)|$. The same method was used in [6,7] for the determination of the Δ production rate in C + C collisions at 4.2 GeV/c per nucleon.

Here, we would like to discuss the role of the higher resonances and comment on our choice of combining only three Breit-Wigner functions for the fitting of the data. There is a number of baryon resonances (more than 10) in the mass region from 1500 MeV/c^2 to 2300 MeV/c^2, with different widths and different contributions to final $(p\pi^+\pi^-)$ states. The masses and widths are known from hadron-hadron interactions and these values were our first guess for the values of free parameters during the fitting procedure. We tried to include a different number of resonances, but the optimum value of the number of resonances was determined from the behavior of the function $\chi^2(a)$. We concluded that the resolution of our experiment is not good enough to extract more than three peaks: the Roper resonance, the $N(1520)$-resonance and the broad distribution positioned at higher mass value which represents the summed contributions of higher baryon resonances.

3 Results and discussion

The minimum of the $\chi^2(a)$ function yields the following value of parameter a: $a = 0.86 \pm 0.05$, *i.e.* the resonance production rate is $R = (14 \pm 5)\%$. Such a result means that $(14 \pm 5)\%$ of the $(p\pi^+\pi^-)$ states in C + C collisions at 4.2 GeV/c per nucleon originate from the decay of the Roper resonance and higher baryon resonances. The uncertainty δa is estimated from the experimental error of the momentum, $\langle \Delta p/p \rangle \leq 10\%$.

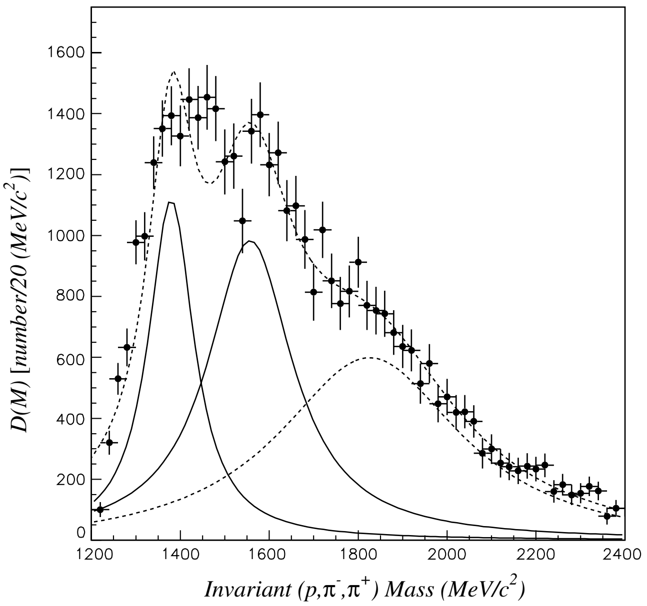

Fig. 2. The difference between invariant-mass distribution and uncorrelated background for $(p\pi^+\pi^-)$ states produced with the best value of parameter a. The full lines represent the $N(1440)$ and $N(1520)$ resonances, while the dashed lines represent higher baryon resonances and the sum of these three Breit-Wigner shapes, respectively.

Table 1. The experimental values for masses and widths of higher baryon resonances in C + C collisions at 4.2 GeV/c per nucleon.

	M (MeV/c^2)	Γ (MeV/c^2)
$N(1440)$	1380 ± 10	130 ± 20
$N(1520)$	1550 ± 20	230 ± 30
The 3rd peak	1810 ± 30	510 ± 40

Figure 2 presents the difference distribution $D(M)$ for $(p\pi^+\pi^-)$ states for the best value of parameter a (dots) together with the fitted functions (lines). The full lines in fig. 2 represent the $N(1440)$ and $N(1520)$ resonances, while the dashed lines represent higher baryon resonances and the sum of these three Breit-Wigner shapes, respectively.

The fitted values for the masses and the widths of the higher baryon resonances are given in table 1. These values confirm the conclusion from [6,7] that in C + C collisions at 4.2 GeV/c per nucleon the resonances masses are practically not shifted towards lower values. However, the Roper resonance width is significantly lower than that for free nucleon collisions. To prove that the obtained small width is stable against the variation of the form of the resonance, we repeated the fitting procedure by using different forms of the Breit-Wigner function (with and without the energy-dependent widths). We found that in all the cases the variations of the resonances widths are smaller than 10% compared to the values given in table 1.

In order to estimate the ratio of the $N(1440)$ and $N(1520)$ resonances decay to $(\Delta\pi)$ and $(p\pi\pi)$ states, we repeated the procedure described above but with an additional cut on the invariant mass of $(p\pi)$ pairs used in the analysis. Among all three-particle states we kept only those combinations where the invariant mass of $(p\pi)$ pairs lies in the mass region of the Δ-resonance ($M_\Delta \pm \Gamma_\Delta$). The values of M_Δ and Γ_Δ are taken from ref. [6]. Figure 3 shows the difference distribution $D(M)$ for $(p\pi^+\pi^-)$ states with an additional cut on the invariant mass of $(p\pi)$ pairs (dots) together with the fitted functions (lines). The parameter a was fixed to the value found in the previous analysis. The values for the mass and the width of the $N(1440)$ and $N(1520)$ resonances in this case are shown in table 2.

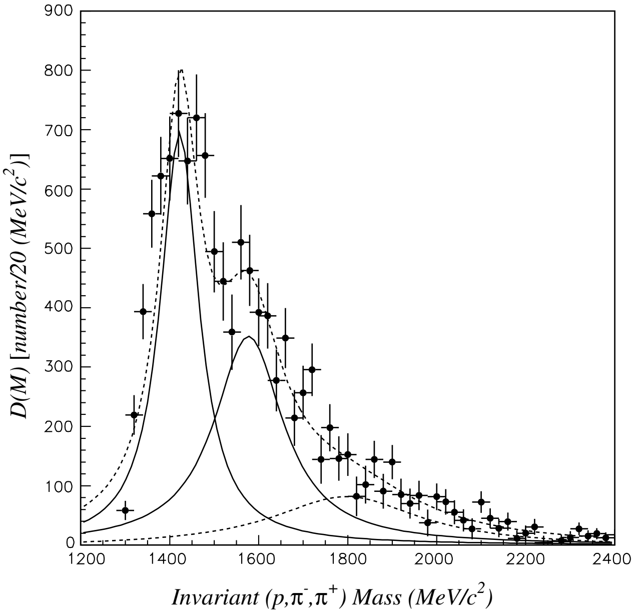

Fig. 3. The difference between invariant-mass distribution and uncorrelated background for $(p\pi^+\pi^-)$ states produced with the best value of parameter a and with a cut on the invariant mass of $(p\pi)$ pairs to be in the Δ-resonance mass region. The full lines represent the $N(1440)$ and $N(1520)$ resonances, while the dashed lines represent higher baryon resonances and the sum of these three Breit-Wigner shapes, respectively.

Table 2. The experimental values for masses and widths of higher baryon resonances in C + C collisions at 4.2 GeV/c per nucleon with a cut on the invariant-mass of $(p\pi)$ pairs to be in the Δ-resonance mass region.

	M (MeV/c^2)	Γ (MeV/c^2)
$N(1440)$	1420 ± 10	105 ± 15
$N(1520)$	1570 ± 20	190 ± 60
The 3rd peak	1790 ± 120	410 ± 90

Comparing fig. 2 and fig. 3, we can see that the Roper peak is much more prominent when the additional cut was used. Also, we can make the qualitative conclusion that higher baryon resonances decay more often directly to $(p\pi^+\pi^-)$ states than through the intermediate $(\Delta\pi)$ state. In the case of the $N(1440)$ and $N(1520)$ resonances this conclusion can be more quantitative by comparing the intensities of the corresponding peaks shown in fig. 2 and fig. 3. This comparison leads to the result that the ratio of the Roper decay to $(\Delta\pi)$ and $(p\pi\pi)$ states is $(52 \pm 5)\%$ and the ratio of the $N(1520)$ decay to $(\Delta\pi)$ and $(p\pi\pi)$ states is $(29 \pm 4)\%$, in good agreement with the results from hadron-hadron interactions [1].

Finally, it was shown in [5] that a consistent description of the data on $\alpha + p$ and $\pi + N$ collisions can be achieved only assuming two structures in the Roper resonance, with only the lower one excited in $\alpha + p$. Comparing our results with those from [5], we can conclude that going from $\pi + N$ through $\alpha + p$ to C + C collisions, the width of the Roper resonance systematically decreases. To confirm this, the data from heavier-nuclei collisions would be very desirable. When discussing the widths of the higher baryon resonances in the two decay channels, it seems that widths are smaller in the $(\Delta\pi)$ than in the $(p\pi\pi)$ channel, but because of relatively small statistics it is impossible to draw final conclusions.

4 Conclusions

The production of the $N(1440)$ and $N(1520)$ resonances in collisions of carbon nuclei with the carbon nucleus at 4.2 GeV/c per nucleon, using a 2 m propane bubble chamber, was studied. From the direct reconstruction of the higher baryon resonances by an invariant-mass analysis of the $(p\pi^+\pi^-)$ states, we obtained the value of the masses and widths of the $N(1440)$ and $N(1520)$ resonances. Our results show that in C + C collisions at 4.2 GeV/c per nucleon the resonances masses are not shifted towards lower values, while the Roper resonance width is lower than that for free nucleon collisions. We also found that $(14 \pm 5)\%$ of the $(p\pi^+\pi^-)$ states in C + C collisions at 4.2 GeV/c per nucleon originate from the decay of the higher baryon resonances. Finally, the ratio of the Roper decay to $(\Delta\pi)$ and $(p\pi^+\pi^-)$ states was estimated to be $(52 \pm 6)\%$, while the ratio of the $N(1520)$ decay to $(\Delta\pi)$ and $(p\pi\pi)$ states is $(29 \pm 4)\%$.

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