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

D. Krpić,[1] G. Škoro,[1] I. Pićurić,[2] S. Backović,[2] and S. Drndarević[1]
[1]Faculty of Physics, University of Belgrade, P.O. Box 368, 11001 Belgrade, Yugoslavia
[2]Faculty of Natural Sciences and Mathematics, University of Montenegro, P.O. Box 211, 81001 Podgorica, Yugoslavia

(Received 1 November 2001; published 4 March 2002)

The production of Δ^0 and Δ^{++} resonances in high energy collisions of carbon nuclei with the carbon nucleus, using a 2-m propane bubble chamber, was investigated. From invariant masses of $(p,\pi^{\pm})$ pairs the masses and widths of the resonances were obtained. The ratios of pion production from delta decays and direct pion creation were estimated, as well as the relative number of nucleons excited to Δ^0 at freeze-out conditions.

DOI: 10.1103/PhysRevC.65.034909 PACS number(s): 25.70.Ef, 14.20.Gk

I. INTRODUCTION

In relativistic nucleus-nucleus collisions a considerable number of pions is produced. Carrying information concerning conditions under which they have been created, these pions are significant for understanding the mechanism of nucleus-nucleus collisions. However, directly produced pions have to be distinguished from those created later, mainly in baryon resonance decays. The decays of Δ resonances are the most important mehanisms of pion production. In the model of independent nucleus-nucleus interactions, the Δ resonance is predominantly created in the reaction $NN\rightarrow\Delta N$, which is concurrent with the processes of direct pion production: $NN\rightarrow NN\pi$, $NN\rightarrow NN\pi\pi$, etc. We analyzed the production proceses of Δ^{++},

$$pp\rightarrow\Delta^{++}n+k\pi \quad (k=0,1,\dots), \tag{1}$$

with the decay $\Delta^{++}\rightarrow p\pi^+$ and production proceses of Δ^0,

$$NN\rightarrow\Delta^0 N+k\pi \quad (k=0,1,\dots), \tag{2}$$

with the decay $\Delta^0\rightarrow p\pi^-$. Several earlier papers [1–3] suggest that the width and mass of the Δ resonances, produced in high energy nucleon collisions and in nucleus-nucleus collisions, could be different. In our previous work [4] we analyzed Δ^{++} production in C+C collisions at 4.2 GeV/c per nucleon. This study, based on relatively small statistics, did not confirm Δ^{++} mass shift to lower values, but we found that the Δ width Γ is slightly lower than that for free nucleon collisions. New experimental verifications [5–10] that the properties of hadrons are modified in dense nuclear matter created in proton-nucleus and nucleus-nucleus collisions led to a mass reduction of $\Delta(1232)$, which explains the interpretation based on the thermal and isobar models [11].

The main intention of this paper is the test of these statements, using new, higher statistics data for carbon-carbon collisions at 4.2 GeV/c per nucleon and comparing the properties of Δ^{++} and Δ^0 reconances produced in such collisions. The paper is organized as follows. The summary of the experimental procedures, as given in Ref. [4], is reproduced in Sec. II. Section III presents the results and discussion. Conclusions are given in Sec. IV.

II. EXPERIMENTAL PROCEDURES

Using the data obtained at the 2-m propane bubble chamber exposed to a ^{12}C beam at Dubna Synhrophasotron, we have studied Δ^{++} and Δ^0 resonance production. At incident momentum of 4.2 GeV/c per nucleon, 20 594 C+C inelastic interactions were selected (compared to 3421 C+C inelastic interactions in our previous work [4]). Practically, all the secondary interactions have been detected in the chamber. To separate π^+ from protons we use momentum-range relations and the detection of $\pi^+\mu^+e^+$ decay. The measured momenta of protons and pions were used to calculate the invariant mass of the $p\pi^{\pm}$ system, M, from the relation

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

where $E_p, E_\pi, \vec{p}_p, \vec{p}_\pi$ are the energy and momentum of the proton and pion, respectively. The invariant mass distribution for (p,π^-) measured pairs is shown in Fig. 1 (solid line). For many of such (p,π) pairs the resulting invariant mass distribution dn/dM contains a large background contribution

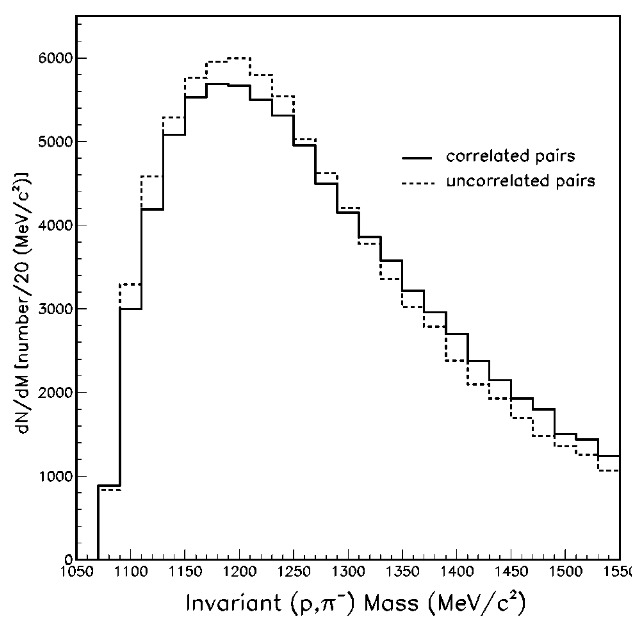

FIG. 1. The invariant mass distribution for (p,π^-) measured pairs in C+C collisions at 4.2 GeV/c per nucleon (solid line) and the background distribution (dashed line).

from uncorrelated pairs (Fig. 1, dashed line). To eliminate their contribution as much as possible, we analyzed the angle between the proton and pion. If the Δ resonance decays in flight, the angle α between the outgoing proton and pion, in the laboratory frame, is defined by

$$\cos\alpha=\frac{1}{p_p p_\pi}\left(E_p E_\pi-\frac{M_\Delta^2-M_\pi^2-M_p^2}{2}\right), \tag{4}$$

where p_p and p_π are proton and pion momenta, E_p and E_π are their energies, and $M_\Delta=1232$ MeV/c^2. We compared this value with the cosine of experimentally measured angle β,

$$\cos\beta=\frac{\vec{p}_p\cdot\vec{p}_\pi}{p_p p_\pi}. \tag{5}$$

The experimental invariant mass distribution, dn/dM for $(p,\pi^\pm)$ pairs was produced using the following criteria:

(1) We kept only the combination satisfying the inequality

$$|\cos\beta-\cos\alpha|<\epsilon, \tag{6}$$

where ϵ is an arbitrary cutoff parameter theoretically lying in the interval [0,2], while, if the momenta of protons and pions are measured with high precision, the upper limit of the interval should be low.

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

(3) The protons emitted from the target carbon nucleus during the process of evaporation were eliminated.

(4) According to relations (1) and (2) the missing mass for proton-pion pairs should be equal to or greater then the nucleon mass.

(5) All events should lie in the kinematically allowed region for NN interactions defined by the Byckling and Kajantie inequality [12]. These criteria should exclude the false, physically uncorrelated proton-pion pairs.

Applying criteria (2) to (5), the initial invariant mass spectrum should be reduced at most by 30%. Only the most important criterion (1). is able to produce much stronger reduction of the spectrum.

A set of experimental spectra dn/dM for $(p,\pi^\pm)$ pairs was produced using various cutoff parameters ϵ. As an example, Fig. 2 (solid line) shows the invariant mass distribution of (p,π^-) pairs for ϵ value: $\epsilon=0.22$. The mass distribution has an obvious maximum. If ϵ is low, the statistics of the invariant mass spectrum in the vicinity of the peak is poor and the effect of the chosen mass of Δ in Eq. (4) is too strong. For higher values of ϵ ($\epsilon>1$), the shape of distribution becomes similar to the distribution obtained without criterion (1). We estimated that the resonable values of ϵ lie in the interval [0.1,0.6]. To check if this peak belongs to the Δ resonance, we performed a Monte Carlo simulation of the background spectrum dn^b/dM including the cutoff criterion (1). This procedure was as follows: We calculated the invariant mass for (p,π) pairs randomly selected using a proton from one event and a pion from another event (event mixing method). We respected the event topology in the way that we combined only events with equal particle multiplicities. This procedure was repeated until the total number of events became equal to the spectrum value; i.e., the background distribution was normalized to the number of pairs in the spectrum. The uncorrelated background, without a sharp peak (Fig. 2, dashed line), is quite different from the distribution obtained by using correlated events, i.e., the experimental spectrum. In order to extract the mass distribution of the resonance, we analyzed the distribution of differences between invariant mass spectra for correlated and uncorrelated pairs, defined by

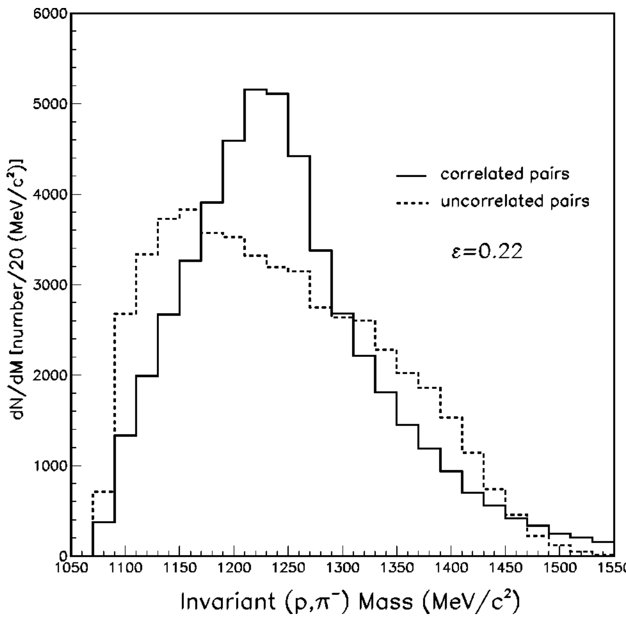

FIG. 2. The invariant mass distribution for (p,π^-) correlated (solid line) and uncorrelated pairs (dashed line) for cutoff parameter $\epsilon=0.22$.

$$D(M)=\frac{dn}{dM}-a\frac{dn^b}{dM}, \tag{7}$$

where a is the normalization factor. The normalization factor is simply connected to the Δ production rate R, which is a ratio of the number of pions that do originate from Δ and from other mechanisms, by the relation

$$R=1-a. \tag{8}$$

We would like to note that difference distribution $D(M)$ may take negative values in some parts of the spectrum. In such a case, we have concluded that the negative part may vary between 1% and 2% of the total positive intensity. Interpreting the distribution $D(M)$ as a pure Δ signal, we have approximated it by a relativistic Breit-Wigner shape [13]

$$b(M)=\frac{\Gamma M M_\Delta}{(M^2-M_\Delta^2)^2+\Gamma^2 M_\Delta^2}, \tag{9}$$

where M_Δ and Γ are the mass and width of the resonance. The data set $D(M)$ for different values of the parameters ϵ

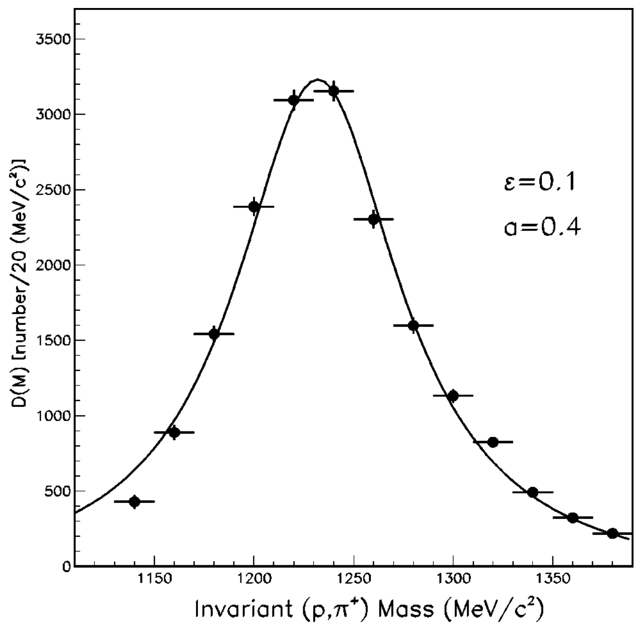

FIG. 3. The difference between invariant mass distribution and uncorrelated background for (p,π^{+}) pairs produced with the best values of parameters ϵ and a. The line represents the fitted function $b(M)$.

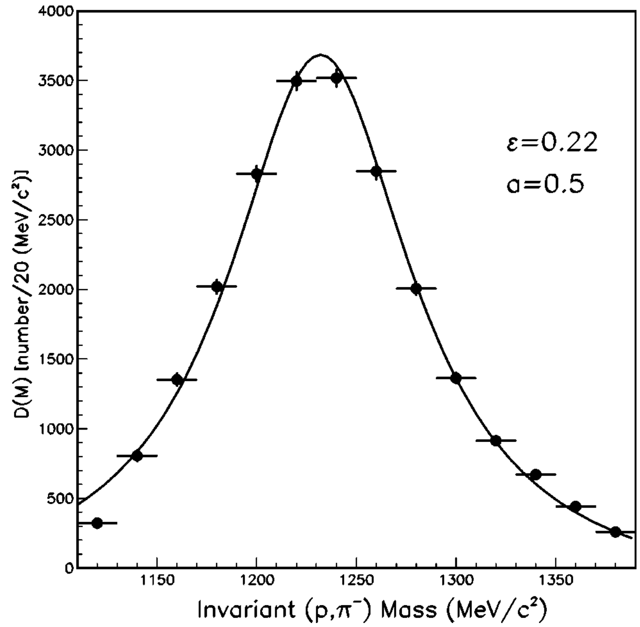

FIG. 4. The difference between invariant mass distribution and uncorrelated background for (p,π^{-}) pairs produced with the best values of parameters ϵ and a. The line represents the fitted function $b(M)$.

and a was fitted by the Breit-Wigner function $b(M)$ and χ^2 was found for each fit. The parameters M_Δ and Γ were determined by minimizing the difference $|D(M)-b(M)|$. In this way we got the set of two parameters for each experimental spectrum produced for chosen values of the parameters ϵ and a.

III. RESULTS AND DISCUSSION

The best values of the parameters ϵ and a were determined from the behavior of the function $\chi^2(\epsilon,a)$. The minimums of χ^2 functions suggest the following values: $\epsilon(\Delta^{++})=0.10\pm0.03$, $\epsilon(\Delta^{0})=0.22\pm0.03$ and $a(\Delta^{++})=0.40\pm0.05$, $a(\Delta^{0})=0.50\pm0.05$. The uncertainty $\delta\epsilon$ is estimated from the experimental error of momentum, $\langle\Delta p/p\rangle \leqslant 10\%$. Figure 3 presents the difference distribution $D(M)$ for (p,π^{+}) pairs for the best values of parameters ϵ and a. The corresponding distribution for (p,π^{-}) pairs is shown in Fig. 4. The experimental values for masses, widths, and production rates of Δ's, obtained by using the best values of parameters, are given in Table I.

The results for Δ^{++} resonance fully agree with our previous results [4] obtained at smaller statistics. The parameters of Δ^{0} resonance production are the new results and we obtained similar values as in the case of Δ^{++} resonance. For both resonances, the mass peak is near the expected position and the Δ width is lower than that for free nucleon collision ($\Gamma=114$ MeV/c^2) [14]. Also, because of the values of errors we are not able to make any conclusion about expected Δ^{0}-Δ^{++} mass and width differences. Finally, the values of rates for Δ production confirm that Δ decay is a dominant mechanism of pion production in C+C collisions at 4.2 GeV/c per nucleon. Similar results are obtained in the case of collisions of heavier nuclei (Ni+Ni and Au+Au) at energies between 1 and 2 A GeV [10].

On the other hand, in Ni+Ni and Au+Au collisions [10], as well as in Ni+Cu collisions [8] at energies between 1 and 2 A GeV, the resonances masses were found to be shifted by an average value of -60 MeV/c^2 relative to the mass distribution of the free Δ resonance. In the case of C-C collisions, we have not found any shift of resonances masses. Such a result is expected if we keep in mind that the absolute shift value is proportional to atomic masses of participant nuclei that became smaller with rising impact parameter [10,11]. For example, in the near-central collisions the shift values are ~-100 MeV/c^2 for Au+Au and ~-50 MeV/c^2 for Ni+Ni nuclei. In our case, the collisions of relatively light nuclei were studied and the results are averaged over all impact parameter values.

On the basis of the results presented above, we estimated the relative number of nucleons excited to Δ^{0} at freeze-out $n(\Delta)/n(\text{nucleon}+\Delta)$. The Δ^{0} abundance $n(\Delta)$ can be obtained by means of the relation [9]

$$n(\Delta)=n(\pi^{-})f_{\text{isobar}}\frac{\pi_{\Delta}^{-}}{\pi_{\text{all}}^{-}}, \tag{10}$$

TABLE I. The experimental values for masses, widths, and production rates of Δ resonances in C+C collisions at 4.2 GeV/c per nucleon.

	M (MeV/c^2)	Γ (MeV/c^2)	R (%)
Δ^{++}	1232 ± 4	85 ± 8	60 ± 5
Δ^{0}	1230 ± 4	93 ± 8	50 ± 5

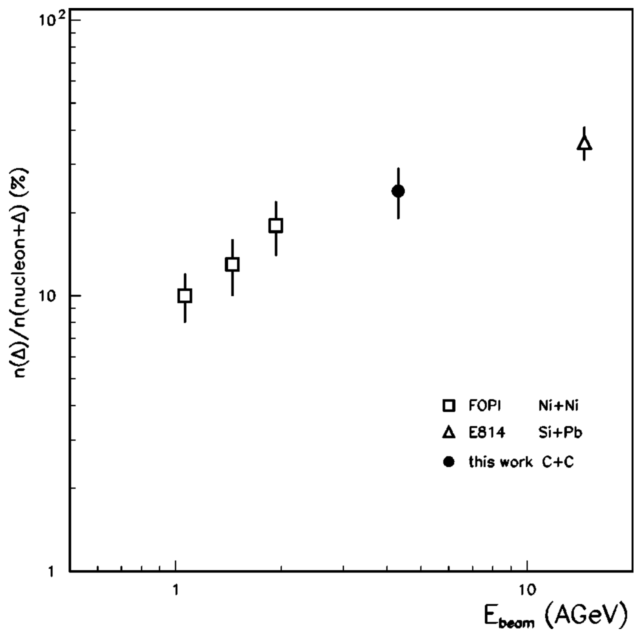

FIG. 5. The relative number of nucleons excited to Δ^0 at freeze-out as a function of the beam energy. The open triangle and squares are the results of the experiments E814 [7] and FOPI [9], respectively.

where $n(\pi^-)$ is the average number of π^- per event, $f_{\rm isobar}$ is the prediction of the isobar model (N is the number of neutrons, Z is the number of protons) [15]:

$$f_{\rm isobar}=\frac{n(\pi^-+\pi^0+\pi^+)}{n(\pi^-)}=\frac{6(Z^2+N^2+NZ)}{5N^2+NZ}, \qquad (11)$$

and $\pi^-_\Delta/\pi^-_{\rm all}$ is our production rate R. The average number of π^- per event in C+C collisions at 4.2 GeV/c per nucleon is $n(\pi^-)_{\rm exp}=1.52\pm0.08$ [16], and this result is in agreement with the prediction of the quark-gluon-string model (QGSM) (see, for example, Refs. [17,18] and references therein) $n(\pi^-)_{\rm QGSM}=1.59$. For $^{12}_{6}$C nucleus $f_{\rm isobar}=3$. Taking into account the production rate $R=(50\pm5)\%$ and the number of participants, nucleons calculated by using $n(\text{nucleon}+\Delta)=2\langle N_p\rangle+\langle n_\Delta\rangle$, where $\langle N_p\rangle=4.32\pm0.07$ is the average participant protons multiplicity in C+C interactions at 4.2 GeV/c per nucleon [19] and $\langle n_\Delta\rangle=0.76$ is average Δ^0 multiplicity, the relative number of nucleons excited to Δ^0 at freeze-out was found to be: $n(\Delta)/n(\text{nucleon})+\Delta)=(24\pm5)\%$. The comparison of this result with the results of E814 Collaboration [7] and FOPI Collaboration [9] is shown in Fig. 5.

IV. CONCLUSIONS

The production od Δ^0 and Δ^{++} 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 direct reconstruction of Δ resonances by an invariant mass analysis of $(p,\pi^\pm)$ pairs, we obtained the values of the masses and widths of the Δ resonances. For both resonances, the mass peak is at the expected position $M_\Delta\sim1232$ MeV/c^2, but the Δ width is lower than for free nucleons collision. The ratios of pion production from Δ decays and direct pion creation were estimated to be at the level of $(50\pm5)\%$ for Δ^0 and $(60\pm5)\%$ for Δ^{++} resonance. It means that Δ decay is a dominant mechanism of pion production in C+C collisions at 4.2 GeV/c per nucleon. Also, the relative number of nucleons excited to Δ^0 at freeze-out is estimated to be $(24\pm5)\%$.

ACKNOWLEDGMENT

We thank the members of the JINR Dubna group that participated in data processing.

[1] D. Contardo *et al.*, Phys. Lett. **168B**, 331 (1986).
[2] V. G. Abeleev *et al.*, Yad. Fiz. **48**, 27 (1988) [Sov. J. Nucl. Phys. **48**, 17 (1988)].
[3] M. Trzaska *et al.*, Darmstat GSI Report No. 61, 1988.
[4] D. Krpić *et al.*, Phys. Rev. C **46**, 2501 (1992).
[5] FOPI Collaboration, D. Pelte *et al.*, Z. Phys. A **357**, 215 (1997).
[6] FOPI Collaboration, D. Pelte *et al.*, Z. Phys. A **359**, 55 (1997).
[7] E814 Collaboration, J. Barrette *et al.*, Phys. Lett. B **351**, 93 (1995).
[8] EOS Collaboration, E. L. Hjort *et al.*, Phys. Rev. Lett. **79**, 4345 (1997).
[9] FOPI Collaboration, B. Hong *et al.*, Phys. Lett. B **407**, 115 (1997).
[10] FOPI Collaboration, M. Eskef *et al.*, Eur. Phys. J. A **3**, 335 (1998).
[11] D. Pelte, nucl-ex/9902006.
[12] B. Byckling and K. Kajantie, *Particle Kinematics* (Wiley, London, 1973), p. 119.
[13] D. Higgins *et al.*, Phys. Rev. D **19**, 731 (1979).
[14] Particle Data Group, D. E. Bloom *et al.*, Eur. Phys. J. C **15**, 1 (2000).
[15] R. Stock, Phys. Rep. **135**, 259 (1986).
[16] N. Agakishiev *et al.*, Z. Phys. C **27**, 177 (1985).
[17] N. S. Amelin *et al.*, Yad. Fiz. **51**, 512 (1990) [Sov. J. Nucl. Phys. **51**, 327 (1990)].
[18] N. S. Amelin *et al.*, Phys. Rev. Lett. **67**, 1523 (1991).
[19] Lj. Simić *et al.*, Phys. Rev. D **34**, 692 (1986).