Production of Δ^0 and Δ^{++} resonances in collisions of ^{4}He nuclei with carbon nuclei at 4.2 GeV/*c* per nucleon

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In conditions of 4π-geometry, the production of Δ^0 and Δ^{++} resonances in collisions of ^{4}He nuclei with carbon nuclei at 4.2 GeV/*c* per nucleon was investigated for the first time. The masses and widths of resonances were obtained based on an analysis of the experimental and background invariant mass distributions of $p\pi^{\pm}$ pairs. The contributions to the pion production from decays of Δ resonances, as well as from direct pion creation, and the relative number of nucleons excited to Δ^0 at freeze-out were estimated. The results obtained were compared to the corresponding data for C+C collisions at the same initial momentum 4.2 GeV/*c* per nucleon.

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It is well known that in relativistic nucleus-nucleus collisions a considerable number of pions are produced, which carry important information on conditions of their formation. Thus the study of pions production represents an interest for understanding the mechanism of nucleus-nucleus collisions. However, one should distinguish between the pions produced directly and those created later, mainly in baryon resonance decays. The decays of Δ resonances are the most important mechanism of pion production [1]. In the model of independent nucleus-nucleus interactions, the Δ resonances are mainly produced in the reaction $NN \to \Delta N$, which competes with the process of direct pion production: $NN \to NN\pi, NN \to NN\pi\pi$, etc. In the present work the production process of Δ^{++},

$$pp \to \Delta^{++} + k\pi (k = 0, 1, \ldots), \quad (1)$$

with the subsequent decay $\Delta^{++} \to p\pi^+$ and the production process of Δ^0,

$$NN \to \Delta^0 N + k\pi (k = 0, 1, \ldots), \quad (2)$$

with the decay $\Delta^0 \to p\pi^-$ were analyzed. Earlier papers [2–9] suggest that the width and mass of the Δ resonances, produced in high energy nucleon collisions and in nucleus-nucleus collisions, could be different, and that the properties of hadrons are modified in dense nuclear matter created in proton-nucleus and nucleus-nucleus collisions, which lead to a mass reduction of $\Delta(1232)$. The latter can be explained by the thermal and isobar models [1,10].

The main goal of this paper is the test of the above-mentioned statements based on the study of production of Δ^0 and Δ^{++} resonances in ^{4}He+C collisions at 4.2 GeV/*c* per nucleon and comparison of their properties with those [1] obtained for C+C collisions at the same initial momentum per nucleon.

The experimental data were obtained using the 2 m propane bubble chamber of the Laboratory of High Energies of JINR (Dubna, Russia) exposed to the beam of relativistic ^{4}He nuclei at Dubna Synchrophasotron. The statistics of the analyzed data consists of 11692 measured ^{4}He+C inelastic events. The methodological questions connected with the processing of the stereo photos, reconstruction of the kinematical characteristics of the secondary particles, their identification, and inclusion of corrections due to the loss of particles emitted under large angle to the object plane of the camera are described in details in [11–14]. The separation of protons (from target) and π^+-mesons was done visually based on their ionization in region $p < 0.8$ GeV/*c*. The elastic events and those from diffractive dissociation of the projectile nucleus were excluded from the analyzed data according to the criteria given in [14].

The measured momenta of protons and pions were used to calculate the invariant mass of the $p\pi^{\pm}$ system, M, from the relation

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

where E_p, E_π, $\vec{p}_p$, $\vec{p}_\pi$ are the energy and momentum of the proton and pion, respectively. The experimental and background invariant mass distribution for $p\pi^-$ pairs are shown in Fig. 1(a). The background spectrum was obtained using the mixed event method. As seen from the figure, for many of the $p\pi^-$ pairs, the invariant mass distribution dn/dM contains a large background contribution from uncorrelated pairs. To reduce their contribution as much as possible, the angle between the proton and pion was analyzed as done in [1]. If the Δ resonance decays in flight, the angle α between the outgoing proton and pion, in the laboratory frame, is defined by

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

where p_p and p_π are the proton and pion momenta, E_p and E_π are the respective energies, and $M_\Delta = 1232$ MeV/c^2. This value was compared with the cosine of experimentally measured angleβ,

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

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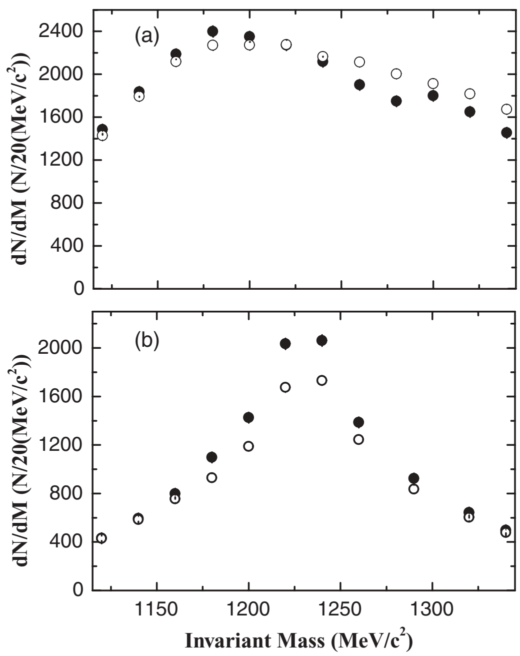

FIG. 1. The invariant mass distribution for $p\pi^-$ pairs for ^{4}He+C collisions at 4.2 GeV/c per nucleon without angular cutoff criteria (a) and using the cutoff parameter $\varepsilon = 0.21$ (b): (•)—experiment, (o)—background.

The experimental invariant mass distribution, dn/dM, for $p\pi^{\pm}$ pairs was constructed using the following criteria:

(i) Only the combinations satisfying the inequality

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

were kept, 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.

(ii) The protons having momenta $p > 3$ GeV/c and emission angles relative to the beam direction $\theta < 4^0$ were treated as spectators and excluded.

(iii) The protons emitted from the target carbon nucleus as a result of evaporation process were eliminated.

(iv) The missing mass for proton-pion pairs should be equal to or greater than the nucleon mass.

(v) All events should lie in the kinematically allowed region for NN collisions defined by the Byckling and Kajantie inequality [15], which should exclude the physically uncorrelated proton-pion pairs.

It should be mentioned that out of all the criteria, the criterion (1) is the most important [1] resulting in the largest reduction of the spectrum.

A set of the experimental spectra dn/dM was constructed for $p\pi^{\pm}$ pairs using different values of cutoff parameter ε. As an example, the invariant mass distribution of $p\pi^-$ pairs using the cutoff parameter $\varepsilon = 0.21$ is shown in Fig. 1(b). The experimental spectrum in Fig. 1(b) differs significantly from that of Fig. 1(a) and has a maximum near $M_\Delta = 1232$ MeV/c^2. At lower ε values ($\varepsilon < 0.1$), the statistics of the invariant mass spectrum becomes poor and the effect of the chosen mass of Δ in Eq. (4) is too strong. For higher values of $\varepsilon(\varepsilon > 1)$, the shape of the invariant mass distribution becomes similar to that obtained without criterion (1). To check if this peak belongs to the Δ resonance, a Monte Carlo simulation of the background spectrum dn^b/dM was performed using the same criteria (1)–(5) as for the experimental distribution. To do this, the invariant mass of $p\pi$ pairs selected randomly using a proton from one event and a pion from another event was calculated. To take into account the events topology, only events with equal particle multiplicities were combined. To make the background distribution as smooth as possible by reducing statistical errors, the number of simulated combinations for each experimental spectrum was at least 6 times as many as that in experiment. Then the background distribution was normalized to the number of pairs in the experimental invariant mass distribution. To extract the mass distribution of the resonance, the distribution of differences between invariant mass spectra for correlated and uncorrelated pairs, given by

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

was analyzed, where a is the normalization factor.

The normalization factor is simply connected to the Δ production rate R, which is the fraction of pions that do originate from Δ, by the relation

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

where a has the meaning of the fraction of pions that originate from other mechanisms. Interpreting the distribution $D(M)$ as a pure Δ signal, it was approximated by a relativistic Breit-Wigner function [16]

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

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 and a was fitted by the Breit-Wigner function $b(M)$ and the value of χ^2 was found for each fit. During these procedures, the parameter ε was varied from the value of 0.1 to 1.0 with the step of 0.01, and a varied from 0.0 to 1.0 with the step of 0.025 for each ε value. The parameters M_Δ and Γ were determined by minimizing the difference $|D(M) - b(M)|$. In this way the set of two parameters was obtained for each experimental spectrum produced for different values of the parameters ε and a.

The best values of the parameters ε and a were determined from an analysis of the behavior of the function $\chi^2(\varepsilon, a)$. The minima of χ^2 functions gave the following values: $\varepsilon(\Delta^{++}) = 0.11 \pm 0.01$, $\varepsilon(\Delta^0) = 0.21 \pm 0.01$, $a(\Delta^{++}) = 0.38 \pm 0.03$, and $a(\Delta^0) = 0.52 \pm 0.03$. The difference distributions $D(M)$ for $p\pi^+$ and $p\pi^-$ pairs using the best values of ε and a are presented in Figs. 2(a) and 2(b), respectively. The experimental values for masses, widths and production rates of Δ resonances for ^{4}He+C collisions at 4.2 GeV/c per nucleon, obtained using the best

TABLE I. The experimental values for masses, widths, and production rates of Δ resonances in ^{4}He+C and C+C collisions at 4.2 GeV/c per nucleon.

Resonance	M (MeV/c^2)		Γ (MeV/c^2)		R (%)	
	^{4}He+C	C+C	^{4}He+C	C+C	^{4}He+C	C+C
Δ^{++}	1228 ± 2	1232 ± 4	65 ± 5	85 ± 8	62 ± 3	60 ± 5
Δ^0	1227 ± 2	1230 ± 4	103 ± 6	93 ± 8	48 ± 3	50 ± 5

values of parameters, are presented in Table I. For comparison, the corresponding results [1] obtained for C+C collisions at the same initial momentum per nucleon are also given in the table.

As seen from Table I, for both resonances the values of M_Δ for ^{4}He+C collisions proved to be slightly shifted by an average value -4 ± 2 MeV/c^2 relative to the mass of the free Δ resonance, which agrees within the errors with the corresponding results for C+C interactions. Our results are not in contradiction with previous results on Ni+Ni and Au+Au [9] and Ni+Cu [7] collisions at energies between 1 and 2 A GeV, where the resonance masses were found to be shifted by an average value -60 MeV/c^2 relative to the mass distribution of the free Δ resonance. Such a small shift observed in the case of ^{4}He+C collisions can be explained by the fact that the absolute shift is roughly proportional to the number of participants that becomes smaller with increasing impact parameter b [1,9,10]. In our case, we study the collisions of the relatively light nuclei and the results are averaged over all impact parameter b values.

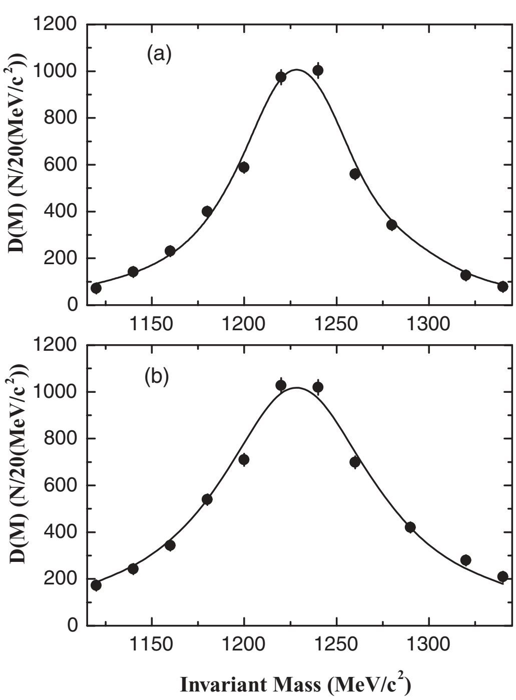

FIG. 2. The difference between the experimental invariant mass distribution and uncorrelated background (•) for $p\pi^+$ (a) and $p\pi^-$ (b) pairs for ^{4}He+C collisions at 4.2 GeV/c per nucleon and the corresponding fits (solid lines) with the best values of parameters ε and a: $\varepsilon(\Delta^{++}) = 0.11 \pm 0.01$, $\varepsilon(\Delta^0) = 0.21 \pm 0.01$, $a(\Delta^{++}) = 0.38 \pm 0.03$, and $a(\Delta^0) = 0.52 \pm 0.03$.

The widths of both resonances were found to be smaller for ^{4}He+C collisions than for free nucleon collision ($\Gamma = 114$ MeV/c^2) [17] and agree with the results for C+C collisions, which points out the noticeable increase of the life time of the Δ resonance in a nucleus. This may be a result of the influence of the nuclear potential on the Δ resonance in the nucleus.

The values of rates R for production of Δ^0 and Δ^{++} resonances for ^{4}He+C collisions coincided within the errors with the corresponding results for C+C collisions, which suggest that R does not depend on the mass number of the projectile-nucleus for these interactions. As seen from Table I, $(62 \pm 3)\%$ and $(48 \pm 3)\%$ of all the π^+- and π^--mesons, respectively, produced in ^{4}He+C collisions are estimated to come from decays of the Δ^{++} and Δ^0 resonance, respectively. This confirms that Δ decay is a dominant mechanism of pion production for ^{4}He+C as well as C+C collisions at 4.2 GeV/c per nucleon. Similar results were obtained for collisions of heavier nuclei (Ni+Ni and Au+Au) at energies between 1 and 2 A GeV [9].

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

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

where $n(\pi^-) = 1.02 \pm 0.03$ [18] is the average number of π^- per event in ^{4}He+C collisions at 4.2 GeV/c per nucleon, $\pi_\Delta^-/\pi_{\text{all}}^-$ is the production rate for Δ^0, $R = (48 \pm 3)\%$, and f_{isobar} is the prediction of the isobar model (N is the number of neutrons, and Z is the number of protons in a nucleus) [19]:

$$f_{\text{isobar}} = \frac{n(\pi^- + \pi^0 + \pi^+)}{n(\pi^-)} = \frac{6(Z^2 + N^2 + NZ)}{5N^2 + NZ}. \tag{11}$$

For ^{4}He and ^{12}C nucleus $f_{\text{isobar}} = 3$. Taking into account the number of participants calculated by using $n(\text{nucleon} + \Delta) = 2\langle N_p \rangle + \langle n_\Delta \rangle$, where $\langle N_p \rangle = 3.06 \pm 0.10$ [20] is the average participant protons multiplicity in ^{4}He+C collisions at 4.2 GeV/c per nucleon, and $n(\Delta) = 0.49$ is average Δ^0 multiplicity for ^{4}He+C collisions, the relative number of nucleons excited to Δ^0 at freeze-out was estimated to be: $n(\Delta)/n(\text{nucleon} + \Delta) = (22 \pm 3)\%$, which coincide within errors with the corresponding result $(24 \pm 5)\%$ obtained for C+C collisions [1] at the same initial momentum per nucleon.

The main conclusions of the present paper can be summarized in the following way. The production of Δ^0 and Δ^{++} resonances in ^{4}He+C collisions at 4.2 GeV/c per nucleon was studied and their properties compared with those obtained for C+C collisions at the same initial momentum per nucleon. From an analysis of the experimental and background invariant mass distributions of $p\pi^{\pm}$ pairs, the values of the masses and widths of the Δ resonances produced in ^{4}He+C collisions were obtained. For both resonances, their widths were found to be noticeably smaller, as in the case of C+C collisions, than for free nucleon collisions. The masses of the resonances were found to be slightly shifted by an average value -4 ± 2 MeV/c^2 compared to the mass of the free nucleon resonance $M_{\Delta} = 1232$ MeV/c^2. The fraction of π^+- and π^--mesons, respectively, coming from Δ resonance decays in ^{4}He+C collisions was estimated to be (62 ± 3)% and (48 ± 3)% for the Δ^{++} and Δ^0 resonance, respectively, and coincided within the errors with the corresponding results for C+C collisions. The values of rates for Δ production confirm that Δ decay is a dominant mechanism of pion production in ^{4}He+C as well as C+C collisions at 4.2 GeV/c per nucleon. The relative number of nucleons excited to Δ^0 at freeze-out was estimated to be (22 ± 3)% for ^{4}He+C collisions at 4.2 GeV/c per nucleon.

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[1] D. Krpic, G. Skoro, I. Picuric, S. Backovic, and S. Drndarevic, Phys. Rev. C **65**, 034909 (2002).

[2] D. Contardo *et al.*, Phys. Lett. **B168**, 331 (1986).

[3] V. G. Ableev *et al.*, Yad. Fiz. **48**, 27 (1998).

[4] FOPI Collaboration, D. Pelte *et al.*, Z. Phys. A **357**, 215 (1997).

[5] FOPI Collaboration, D. Pelte *et al.*, Z. Phys. A **359**, 55 (1997).

[6] E814 Collaboration, J. Barrette *et al.*, Phys. Lett. **B351**, 93 (1995).

[7] EOS Collaboration, E. L. Hjort *et al.*, Phys. Rev. Lett. **79**, 4345 (1997).

[8] FOPI Collaboration, B. Hong *et al.*, Phys. Lett. **B407**, 115 (1997).

[9] FOPI Collaboration, M. Eskef *et al.*, Eur. Phys. J. A **3**, 335 (1998).

[10] D. Pelte, arXiv:nucl-ex/9902006v1.

[11] A. U. Abdurakhimov *et al.*, JINR Communications P1-6277 (1972).

[12] G. N. Agakishiev *et al.*, JINR Communications P1-84-235 (1984).

[13] I. A. Ivanovskaja *et al.*, JINR Communications P1-91-264 (1991).

[14] A. I. Bondarenko *et al.*, JINR Communications P1-98-292 (1998).

[15] B. Byckling and K. Kajantie, *Particle Kinematics* (Wiley, London, 1973), p. 119.

[16] D. Higgins *et al.*, Phys. Rev. D **19**, 731 (1979).

[17] Particle Data Group, D. E. Groom *et al.*, Eur. Phys. J. C **15**, 1 (2000).

[18] N. Angelov *et al.*, Yad. Fiz. **33**, 1046 (1981).

[19] R. Stock, Phys. Rep. **135**, 259 (1986).

[20] Armutljiski *et al.*, JINR Communications P1-86-263 (1986).