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Production of baryon resonances in $\pi^- + ^{12}C$ interactions at 40 GeV/c

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In conditions of 4π-geometry, the production of Δ^{++} and Δ^0 resonances in $\pi^- + ^{12}C$ interactions at 40 GeV/c was investigated for the first time. The masses and widths of resonances were obtained from an analysis of the experimental and background invariant mass distributions of $p\pi^\pm$ pairs. The fractions of charged pions coming from Δ^{++} and Δ^0 decay as well as the inclusive cross-section of Δ^{++} and Δ^0 production were determined. The results obtained were compared to the recent results on $\Delta(1232)$ production in ^{4}He+C and C+C collisions at 4.2 GeV/c per nucleon, and Ni+Ni and Au+Au collisions at energies between 1 and 2A GeV.

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I. INTRODUCTION

The study of non-nucleon degrees of freedom in nuclei is one of the fundamental problems in modern nuclear physics. Much has been made from discovery of the proton-neutron composition of a nucleus, quasinucleons, pions to pion and baryon resonances, partons, quarks, and gluons, which has widely enlightened many scientific and popular works and reviews. Concerning the baryon resonances, the production of the $\Delta(1232)$ resonance remains the topic of interest for experimenters as well as theoreticians nowadays. Firstly, this is because the Δ resonance can be excited in various strong and electromagnetic processes induced by pions, nucleons, nuclei, photons, and electrons. Secondly, the results on production of the Δ resonance are nontrivial and there is variety in their theoretical interpretations, which are mainly ambiguous.

The process responsible for meson production in central heavy ion collisions at relativistic energies is believed to be predominantly the excitation of baryon resonances during the early compression phase of the collision [1]. In the later expansion phase these resonances decay. In total, the average mass of the excited baryon resonances and the number of pions produced by their decay chains increase with bombarding energy [1]. This mechanism is the basic process of pion production which is used in nuclear transport models to describe the dynamics of relativistic heavy ion collisions [2–9]. The experimental results on excitation of the Δ resonance in heavy ion collisions can be found, for example, in [1,10–13]. The main result from these studies was that the width and mass of the Δ resonance produced in heavy ion collisions differed significantly from those of the free $\Delta(1232)$ resonance, and that the properties of hadrons are modified in dense hadron matter created in nucleus-nucleus collisions, which led to a significant mass reduction of $\Delta(1232)$. The latter can be explained by the thermal and isobar models [1,14].

Most experiments on production of the $\Delta(1232)$ resonance in light nuclei were conducted at energies ranging from the threshold of $\Delta(1232)$ production ($\sim$650 MeV/nucleon) to several GeV/nucleon. Many of these experiments, e.g., [15–21], belonged to studies of Δ production in dependence on the energy transfer $Q = E_0 - E_t$ in $A(^3\text{He}, t)$ charge exchange reaction with various light target nuclei. In early works [15,16] it was shown that the cross-section peak at $Q \approx 300$ MeV due to the $\Delta(1232)$ excitation was shifted to the lower Q values than the respective peak in the $p(^3\text{He}, t)\Delta^{++}$ reaction. This shift was confirmed in the following experiments [21–25] and associated with the collective (non-nucleon) excitation of the Δ resonance in nuclei.

The identification of structures in the invariant mass distribution of correlated proton and pion pairs provides the direct proof that nucleons are excited to high-lying resonances [1]. The major obstacle that should be overcome in reconstructing the invariant mass is the large background of noncorrelated $p\pi$ pairs [1]. In peripheral reactions with very light projectiles, e.g., p [26,27] or ^{3}He [28] induced reactions at around 2 GeV bombarding energy, the $p\pi$ correlations were successfully analyzed and the mass distribution of the $\Delta(1232)$ resonance was determined. The resonance mass was found to be shifted by about –25 MeV/c^2 to lower masses in reactions on various targets, compared to those on protons [26–28]. The mass reduction of the Δ resonance in $p + A$ collisions ($A =$ C, Nb, Pb) at 0.8 and 1.6 GeV incident energy [26] was traced back to the effects of Fermi motion, NN scattering and pion reabsorption in nuclear matter.

Nevertheless, in spite of a variety of data on the $\Delta(1232)$ production in light nuclei collisions, there are hardly any analyses made under conditions of 4π-geometry on reconstructing the invariant mass of the $\Delta(1232)$ resonance produced at projectile energies $E_0 > 10$ GeV per nucleon. This analysis would be interesting, since it would allow one to study the properties of the $\Delta(1232)$ resonance produced at energies much higher than the threshold of $\Delta(1232)$ production. On the other hand, for the light target nucleus such as ^{12}C and the projectile pion energy as high as 40 GeV the contribution from $\Delta N \to NN$ decay mode of the Δ resonance in the nucleus should be small enough so that the inclusive cross section of $\Delta(1232)$ production is determined predominantly by the $\Delta \to N\pi$ decay channel. For example, in $^2\text{H}(^3\text{He}, t)$ reaction at 2 GeV projectile energy [29], the yield of the exclusive $^2\text{H}(^3\text{He}, t)2p$ reaction in the region of $\Delta(1232)$ excitation was found to be less than 10% of the inclusive $^2\text{H}(^3\text{He}, t)$ cross section, which indicates the small contribution of the $\Delta N \to NN$ process.

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The main aim of this paper is the study of production of Δ^{++} and Δ^0 resonances in π^-+^{12}C interactions at 40 GeV/c and comparison of their properties with the recent results on Δ production in ^{4}He+C and C+C collisions [30,31] at 4.2 GeV/c per nucleon, and near-central Ni+Ni and Au+Au collisions [1, 32] at energies between 1 and 2A GeV. The paper is organized as follows. The summary of the experimental procedures is given in Sec. II. Section III presents the results and discussion, and conclusions are given in Sec. IV.

II. EXPERIMENTAL PROCEDURES

The experimental data were obtained using the 2 m propane bubble chamber of the Laboratory of High Energies of JINR (Dubna, Russia) exposed to a beam of relativistic π^--mesons at 40 GeV/c at Serpukhov Accelerator. The statistics of the analyzed data consists of 16865 measured π^-+^{12}C inelastic events corresponding to the cross section 179 ± 2 mb [33,34]. The methodological issues connected with the processing of the stereo photos, selection and identification of types of interactions in propane (C_3H_8), 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 [35–37]. The separation of protons and π^+-mesons was done visually based on their ionization in region $p < 0.8$ GeV/c. The analysis on δ-electrons showed that the admixture of protons among the fast positive singly charged particles identified as π^+-mesons was $12 \pm 5\%$ of the measured mean multiplicity of protons [34]. It should be mentioned that π^--mesons make up the main fraction ($> 95\%$) among the negatively charged particles [34].

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

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

where E_p, E_π, $\vec{p}_p$, $\vec{p}_\pi$ are the energy and momentum of the proton and pion, respectively. The experimental invariant mass distributions for $p\pi^+$ and $p\pi^-$ pairs in π^-+^{12}C interactions at 40 GeV/c are shown in Fig. 1. The experimental distribution was obtained combining protons and pions in each individual event. As seen from the figure, the invariant mass distribution dN/dM for both $p\pi^+$ and $p\pi^-$ pairs does not show a resonance-like structure near $M_\Delta = 1232$ MeV/c^2. This is, as was shown earlier for C+C and ^{4}He+C collisions at 4.2A GeV/c [30,31], due to a large background contribution from uncorrelated $p\pi$ pairs. To reduce their contribution as much as possible, the method of analyzing the angle between the proton and pion was used as done successfully in [30,31] to extract the mass distribution of the Δ resonance. In this work, this method is developed further to determine the inclusive cross-section of production of the Δ resonance along with its mass and width in π^-+^{12}C interactions at 40 GeV/c. If the Δ resonance decays in flight, the angle α between the outgoing proton and pion, in the laboratory frame, is defined by

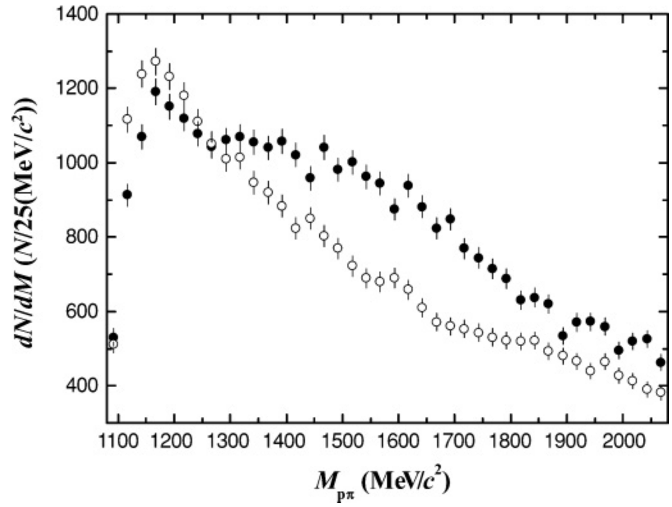

FIG. 1. The experimental invariant mass distribution for $p\pi^+$ ($\bullet$) and $p\pi^-$ ($\circ$) pairs in π^-+^{12}C interactions at 40 GeV/c.

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

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 angle β,

$$\cos\beta = \frac{\vec{p}_p \cdot \vec{p}_\pi}{p_p p_\pi}. \qquad (3)$$

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

$$|\cos\beta - \cos\alpha| < \varepsilon \qquad (4)$$

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 emitted from the target carbon nucleus as a result of evaporation process were eliminated.

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

It should be mentioned that out of all the criteria, the criterion (i) is the most important [30,31] 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 experimental and background invariant mass distributions of $p\pi^+$ and $p\pi^-$ pairs using the cutoff parameter $\varepsilon = 0.63$ and $\varepsilon = 0.57$, respectively, are shown in Figs. 2(a) and 2(b), respectively. The background spectrum was obtained by a Monte Carlo method using the same criteria (i)–(iii) as for the experimental distribution. That is, the invariant mass of $p\pi$ pairs selected randomly using a proton from one event and a pion from another event was

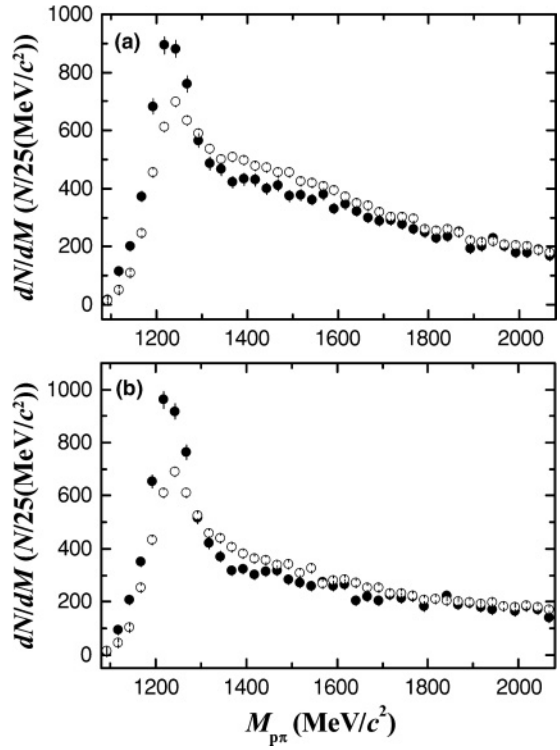

FIG. 2. The invariant mass distributions for $p\pi^+$ (a) and $p\pi^-$ (b) pairs in π^-+^{12}C interactions at 40 GeV/c using the cutoff parameter $\varepsilon = 0.63$ and $\varepsilon = 0.57$, respectively: (•) – experiment, (○) – background. The background distribution is normalized to the total number of pairs in experiment.

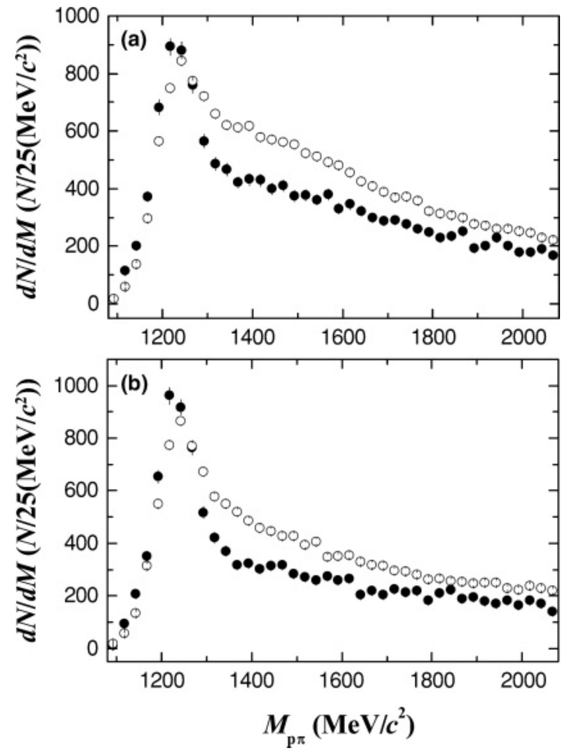

FIG. 3. The same as in Fig. 2, but here the background distribution in region 1105–1355 MeV/c^2 is normalized to the number of pairs in the experimental distribution in the same region.

calculated. To take into account the event 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 5 times as many as that in experiment. Then the background spectrum was normalized to the total number of pairs in the experimental invariant mass distribution. The experimental spectra in Fig. 2 differ significantly from those of Fig. 1 and have a maximum near $M_\Delta = 1232$ MeV/c^2. At lower ε values ($\varepsilon < 0.2$), the statistics of the invariant mass spectrum becomes poor and the effect of the chosen mass of Δ in Eq. (2) is too strong. For higher values of ε ($\varepsilon > 1.1$), the shape of the invariant mass distribution becomes similar to that obtained without criterion (i). To extract the mass distribution of the resonance and obtain the best background distribution for each ε value the following procedures were performed. First, the background distribution in region 1105–1355 MeV/c^2 was normalized to the number of pairs in the experimental distribution in the same region. The resulting background distribution $\frac{dn^b}{dM}$ along with the experimental spectrum $\frac{dn^{\exp}}{dM}$ for $p\pi^+$ and $p\pi^-$ pairs using the cutoff parameter $\varepsilon = 0.63$ and $\varepsilon = 0.57$, respectively, is shown in Figs. 3(a) and 3(b), respectively. Then, the distribution of differences between experimental and background invariant mass distribution, given by

$$D(M) = \frac{dn^{\exp}}{dM} - a\frac{dn^b}{dM} \qquad (5)$$

was analyzed, where a is the coefficient varying from 0 to 1.

Interpreting the distribution $D(M)$ as a pure Δ signal, it was approximated in region 1105–1355 MeV/c^2 by a relativistic Breit-Wigner function [38]

$$b(M) = \frac{\Gamma M M_\Delta}{\left(M^2 - M_\Delta^2\right)^2 + \Gamma^2 M_\Delta^2}, \qquad (6)$$

where M_Δ and Γ are the mass and width of the resonance. The data set $D(M)$ for different values of 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 1.1 with the step of 0.01, and a varied from 0.0 to 1.0 with the step of 0.01 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 parameters ε and a.

The best values of 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: $\varepsilon(\Delta^{++}) = 0.63 \pm 0.01$, $\varepsilon(\Delta^0) = 0.57 \pm 0.01$, $a(\Delta^{++}) = 0.63 \pm 0.01$, and $a(\Delta^0) = 0.56 \pm 0.01$. The difference distributions $D(M)$ for $p\pi^+$ and $p\pi^-$ pairs, using the best values of ε and a, along with the corresponding Breit-Wigner fits are presented in Figs. 4(a) and 4(b), respectively, from where the mass and width of the Δ^{++} and Δ^0 resonance

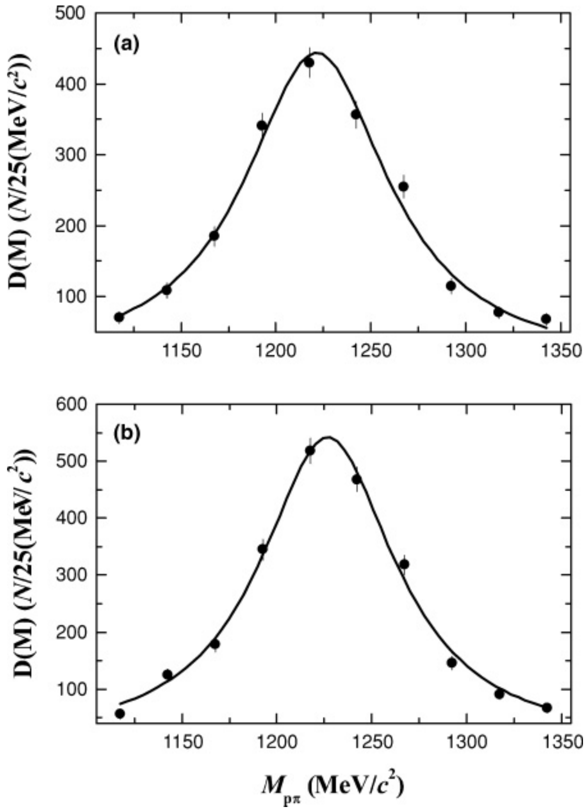

FIG. 4. The difference (•) between the experimental invariant mass distribution and background for $p\pi^+$ (*a*) and $p\pi^-$ (*b*) pairs in π^-+^{12}C interactions at 40 GeV/*c* and the corresponding Breit-Wigner fits (solid lines) at the best values of parameters ε and a: $\varepsilon(\Delta^{++}) = 0.63 \pm 0.01$, $\varepsilon(\Delta^0) = 0.57 \pm 0.01$, $a(\Delta^{++}) = 0.63 \pm 0.01$, and $a(\Delta^0) = 0.56 \pm 0.01$.

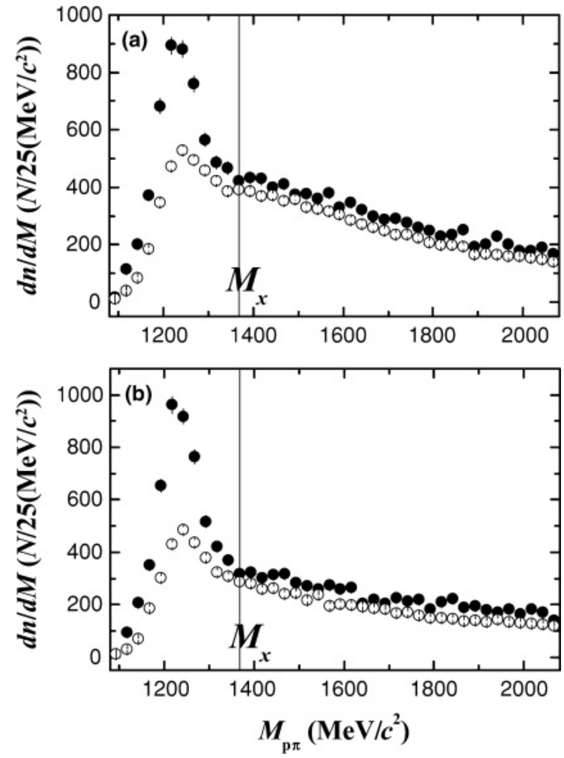

FIG. 5. The corresponding experimental invariant mass distribution $\frac{dn^{\exp}}{dM}$ (•) and the best background distribution $a\frac{dn^b}{dM}$ (○) for $p\pi^+$ (*a*) and $p\pi^-$ (*b*) pairs in π^-+^{12}C interactions at 40 GeV/*c* using the best values of ε and a.

produced in π^-+^{12}C interactions at 40 GeV/*c* were obtained. The corresponding experimental invariant mass distribution $\frac{dn^{\exp}}{dM}$ and the best background distribution $a\frac{dn^b}{dM}$ for $p\pi^+$ and $p\pi^-$ pairs using the best values of ε and a are shown in Figs. 5(a) and 5(b), respectively. As seen from the figure, both Δ^{++} and Δ^0 resonance contribute to the experimental spectrum in region from $M_{p\pi} \sim M_p + M_\pi$ till $M_{p\pi} = M_x \sim 1370$ MeV/c^2, where the experimental spectrum equals within errors to background. The slight excess of the experimental spectra over the background in region $M_{p\pi} > 1400$ MeV is due to the contribution from higher-lying resonances, the closest of which is the $N^*(1440)$ resonance [39]. It should be noted that the contribution from higher-lying resonances is highly suppressed by the criterion (i) and their intensity goes to zero as $\varepsilon \to 0$. As seen from Figs. 5(a) and 5(b), in our case, for $\varepsilon = 0.63$ and $\varepsilon = 0.57$ values the intensity of higher-lying resonances is small enough so that they do not contribute in region of the Δ resonance $M_{p\pi} < M_x$. To determine the fraction of π^+ and π^--mesons coming from Δ^{++} and Δ^0 resonance decay, respectively, relative to the total number of π^+ and π^--mesons, respectively, produced in π^-+^{12}C interactions at 40 GeV/*c*, the following formulae were applied using the above obtained best experimental and background spectra:

$$R(\pi^+/\Delta^{++}) = \frac{k \cdot \int_{M_p+M_\pi}^{M_x} \left(\frac{dn^{\exp}}{dM} - a \cdot \frac{dn^b}{dM}\right) dM}{\int_{M_p+M_\pi}^{\infty} \frac{dn^{\exp}}{dM} dM} \times \frac{N_p \cdot n_p(\pi^+)}{N_{\text{tot}} \cdot n(\pi^+)}, \quad (7)$$

where $R(\pi^+/\Delta^{++})$ is the fraction of π^+-mesons coming from Δ^{++} decay, $k = 1.05$ is the correction factor accounting for "artificial" increase of the total number of $p\pi^+$ combinations in experiment due to some admixture of protons among fast π^+-mesons which cause the appearance of "wrong" $p\pi^+$ pairs, $N_p = 8468$ is the number of π^-+^{12}C events with the proton yield and $n_p(\pi^+) = 3.37 \pm 0.04$ is the mean number of π^+-mesons per event in these events, $N_{\text{tot}} = 16865$ is the total number of π^-+^{12}C events and $n(\pi^+) = 3.10 \pm 0.02$ [34] is the mean number of π^+-mesons per event in π^-+^{12}C interactions at 40 GeV/*c*; and analogously for the fraction of π^--mesons coming from Δ^0 decay we have

$$R(\pi^-/\Delta^0) = \frac{\int_{M_p+M_\pi}^{M_x} \left(\frac{dn^{\exp}}{dM} - a \cdot \frac{dn^b}{dM}\right) dM}{\int_{M_p+M_\pi}^{\infty} \frac{dn^{\exp}}{dM} dM} \cdot \frac{N_p \cdot n_p(\pi^-)}{N_{\text{tot}} \cdot n(\pi^-)}, \quad (8)$$

where $n_p(\pi^-) = 3.44 \pm 0.04$ is the mean number of π^--mesons per event in events with the proton yield, and $n(\pi^-) = 3.22 \pm 0.02$ [34] is the mean number of π^--mesons per event in π^-+^{12}C interactions at 40 GeV/*c*. Knowing $R(\pi/\Delta)$

TABLE I. The experimental values for masses, widths, production rates, $R(\pi/\Delta)$, and inclusive cross sections of production of Δ resonances in π^-+^{12}C interactions at 40 GeV/c.

Resonance	M(MeV/c^2)	Γ(MeV/c^2)	$R(\pi/\Delta)$(%)	$\sigma(\Delta)$(mb)
Δ^{++}	1220 ± 3	92 ± 8	5.7 ± 0.8	32 ± 5
Δ^0	1226 ± 3	87 ± 7	6.1 ± 0.9	105 ± 16

and taking into account the different isospin channels of the Δ resonance decay using the respective Clebsh-Gordan coefficients [39] ($\Delta^{++} \to 1 \cdot (p + \pi^+)$ and $\Delta^0 \to \frac{2}{3} \cdot (n + \pi^0) + \frac{1}{3} \cdot (p + \pi^-)$), one can determine the inclusive cross-section of Δ^{++} and Δ^0 production in π^-+^{12}C interactions at 40 GeV/c defined by

$$\sigma(\Delta^{++} \to p\pi^+) = R(\pi^+/\Delta^{++}) \cdot n(\pi^+) \cdot \sigma_{\text{in}}(\pi^- + {}^{12}\text{C}), \quad (9)$$

and

$$\sigma(\Delta^0 \to N\pi) = 3 \cdot R(\pi^-/\Delta^0) \cdot n(\pi^-) \cdot \sigma_{\text{in}}(\pi^- + {}^{12}\text{C}), \quad (10)$$

where the coefficient in the latter formula accounts for the $\Delta^0 \to n + \pi^0$ decay channel of the Δ^0 resonance which is realized twice more often than $\Delta^0 \to p + \pi^-$ channel, $n(\pi^+) = 3.10 \pm 0.02$ and $n(\pi^-) = 3.22 \pm 0.02$ [34] is the mean number of π^+ and π^--mesons per event in $\pi^- + {}^{12}$C interactions at 40 GeV/c, and $\sigma_{\text{in}}(\pi^{-12}\text{+C}) = 179 \pm 2$ mb [33,34] is the inelastic cross section of π^-+^{12}C interactions at 40 GeV/c. The error in determination of the fraction of pions coming from Δ decay and inclusive cross-section of Δ production was estimated to be $\sim$15% and is mainly caused by uncertainties due to some admixture of protons among fast π^+-mesons.

III. RESULTS AND DISCUSSION

The experimental values for masses, widths, production rates, $R(\pi/\Delta)$, and inclusive cross sections of production of Δ resonances for π^-+^{12}C interactions at 40 GeV/c, obtained using the best values of ε and a, are presented in Table I. As seen from Table I, the mass of the Δ^{++} and Δ^0 resonance, respectively, was shifted by $\Delta m_\Delta = -12 \pm 3$ and -6 ± 3 MeV/c^2, respectively, relative to the mass of the free $\Delta(1232)$ resonance. As seen from Table II, the average mass shift of the Δ resonance, $\Delta m_\Delta = -9 \pm 3$ MeV/c^2, produced in π^-+^{12}C interactions at 40 GeV/c agrees well with the result of the theoretical work by Weinhold *et al.* [1,40], in which the mass of the $\Delta(1232)$ resonance was calculated to be shifted by $\Delta m_\Delta \approx -10$ MeV/c^2 when corrections due to the nucleon interaction in the πN loop of the Δ self-energy are taken into account. This agreement was to be expected, because in π^-+^{12}C interactions at 40 GeV/c the Δ resonance is excited in the light carbon nucleus at normal hadronic densities and the change of the nuclear environment (potential) due to the light pion projectile is insignificant compared to that in nucleus-nucleus collisions. The situation with respect to relativistic nucleus-nucleus collisions, especially in case of heavy ions, is different and more complex. This is because of the dense nuclear matter created in nucleus-nucleus collisions in which the properties of the Δ resonance can modify significantly [1,14,23,32]. As was pointed out in [1], there are two conceivable causes for these modifications: The resonance masses are shifted because of their nuclear environment or/and the resonances are in thermal equilibrium with the hadronic matter at a low temperature [1]. The environment causes in general a mass shift which can be either positive or negative and depends on the hadronic density [1]. For example, as seen from Table II, for near-central Ni+Ni and Au+Au collisions [1,32] at energies between 1 and 2A GeV the average mass shift of the Δ resonance was about -60 and -80 MeV/c^2, respectively. The mass shift of the Δ resonance in nucleus-nucleus collisions was found to be roughly proportional to the number of participants that becomes smaller with increasing impact parameter b [1,13,14]. The small mass shift of the Δ resonance for ^{4}He+C collisions and almost no shift observed for C+C collisions at 4.2A GeV/c, as seen from Table II, was explained by the fact that the colliding nuclei were light and the results averaged over all impact parameter b values [30,31].

TABLE II. The average mass shift and width of the Δ resonance in π^-+^{12}C interactions at 40 GeV/c, ^{4}He+C and C+C collisions at 4.2 GeV/c per nucleon, and near-central Ni+Ni and Au+Au collisions at energies between 1 and 2A GeV.

Type	$\langle\Delta m_\Delta\rangle$(MeV/c^2)	$\langle\Gamma_\Delta\rangle$(MeV/c^2)
π^-+^{12}C, 40 GeV/c	-9 ± 3	89 ± 8
^{4}He+C, 4.2A GeV/c	-4 ± 2	84 ± 6
C+C, 4.2A GeV/c	-1 ± 4	89 ± 8
Ni+Ni, 1.06A GeV	-59 ± 10	48 ± 5
Ni+Ni, 1.45A GeV	-52 ± 10	49 ± 5
Ni+Ni, 1.93A GeV	-59 ± 10	48 ± 5
Au+Au, 1.06A GeV	-78 ± 10	44 ± 5

As seen from Table I, the widths of both Δ^{++} and Δ^0 resonance, produced in π^-+^{12}C interactions at 40 GeV/c, coincided within errors and were found to be noticeably lower than that of the free Δ resonance ($\Gamma = 115$ MeV/c^2) [39]. As shown in Table II, the average widths of the Δ resonance for collisions of π^--mesons at 40 GeV/c, ^{4}He, and C nuclei at 4.2A GeV/c with the target carbon nucleus coincided within errors, being independent of the mass and energy of the light projectile nucleus (particle). It should be noted that the average width of the Δ resonance for Ni+Ni collisions, as seen from Table II, proved also to be the same within errors for energies between 1 and 2A GeV and was approximately twice as low as that in carbon involved interactions. The significant decrease of the mass and width of the Δ resonance when going from light nuclei to near-central heavy ion collisions can be explained by the significant difference between hadronic densities (nuclear environment) in light nuclei collisions and those in near-central heavy ion collisions.

As seen from Table I, the fraction of π^+ and π^--mesons coming from Δ^{++} and Δ^0 resonance decay, respectively, in π^-+^{12}C interactions at 40 GeV/c coincided within errors and proved to be 6 ± 1%, on the average. This value is much smaller than the corresponding result for ^{4}He+C collisions and C+C collisions at 4.2A GeV/c, and Ni+Ni and Au+Au collisions [1,30–32] at energies between 1 and 2A GeV, where at least 50% of pions were estimated to come from decay of Δ^{++} and Δ^0 resonance. This was to be expected, since at projectile energies as high as 40 GeV, as compared to energies of the order of several GeV per nucleon, more channels open up for the favorable production of other higher mass resonances as well as ρ^0, ω^0, and f^0-mesons [41–43]. In early works [42,43] it was shown that approximately 30% of charged pions produced in π^-+^{12}C interactions at 40 GeV/c come from ρ^0, ω^0, and f^0-meson decay. The inclusive cross section of production of ρ^0, ω^0, and f^0-mesons in π^-+^{12}C interactions at 40 GeV/c proved to be 70.5 ± 7.5, 75.0 ± 9.0, and 7.5 ± 7.5 mb, respectively [42,43]. As seen from Table I, the inclusive cross section of Δ^{++} and Δ^0 production (32 ± 5 and 105 ± 16 mb, respectively) was found to be of the same order with that of ρ^0, ω^0, and f^0-mesons in π^-+^{12}C interactions at 40 GeV/c. Approximately triple excess of the inclusive cross-section of Δ^0 production over that of Δ^{++} in π^-+^{12}C interactions at 40 GeV/c can probably be due to the negative charge of the projectile pion.

IV. CONCLUSIONS

The main conclusions of the present paper can be summarized in the following way. The production of Δ^{++} and Δ^0 resonances in π^-+^{12}C interactions at 40 GeV/c was investigated for the first time and their properties compared with those obtained for ^{4}He+C and C+C collisions at 4.2A GeV/c, and near-central Ni+Ni and Au+Au collisions at energies between 1 and 2A GeV. From an analysis of the experimental and background invariant mass distributions of $p\pi^\pm$ pairs, the values of the masses, widths, production rates, $R(\pi/\Delta)$, and inclusive cross sections of production of Δ resonances in π^-+^{12}C interactions at 40 GeV/c were determined. The masses and widths of Δ resonances differed noticeably from those of the free $\Delta(1232)$ resonance.

The average mass shift of the Δ resonance, $\Delta m_\Delta = -9 \pm 3$ MeV/c^2, produced in π^-+^{12}C interactions at 40 GeV/c agreed well with the result of theoretical calculations in which the mass of the $\Delta(1232)$ resonance was found to be shifted by $\Delta m_\Delta \approx -10$ MeV/c^2 when corrections due to the nucleon interaction in the πN loop of the Δ self energy are taken into account.

The widths of both Δ^{++} and Δ^0 resonance (92 ± 8 and 87 ± 7 MeV/c^2, respectively), produced in π^-+^{12}C interactions at 40 GeV/c, coincided within errors and were found to be noticeably lower than that of the free $\Delta(1232)$ resonance ($\Gamma = 115$ MeV/c^2). The average widths of the Δ resonance for collisions of π^--mesons at 40 GeV/c, ^{4}He, and C nuclei at 4.2A GeV/c with the target carbon nucleus coincided within errors, being independent of the mass and energy of the light projectile nucleus (particle). The mass and width of the Δ resonance produced in near-central Ni+Ni and Au+Au collisions at energies between 1 and 2A GeV were significantly lower than those of the Δ resonance produced in π^-+^{12}C interactions at 40 GeV/c, ^{4}He+C and C+C collisions at 4.2 GeV/c per nucleon, which is due to the significant difference between hadronic densities (nuclear environment) in light nuclei collisions and those in near-central heavy ion collisions.

The fraction of π^+ and π^--mesons coming from Δ^{++} and Δ^0 resonance decay, respectively, in π^-+^{12}C interactions at 40 GeV/c coincided within errors and proved to be 6 ± 1%, on the average. The inclusive cross-section of Δ^{++} and Δ^0 production (32 ± 5 and 105 ± 16 mb, respectively) was found to be of the same order with that of ρ^0, ω^0, and f^0-mesons in π^-+^{12}C interactions at 40 GeV/c. Approximately triple excess of the inclusive cross section of Δ^0 production over that of Δ^{++} in π^-+^{12}C interactions at 40 GeV/c is probably due to the negative charge of the projectile pion.

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