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Δ^0 resonance production in peripheral 4.2*A* GeV C + Ta collisions

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The production of $\Delta^0(1232) \rightarrow p\pi^-$ resonance is studied in peripheral C + Ta collisions at 4.2*A* GeV using the 2-m propane bubble chamber exposed at JINR Dubna Synchrophasotron. Using an invariant mass distribution of $p\pi^-$ pairs and additional kinematical constrains, the mass, width, and kinematical characteristics of Δ^0 resonance are determined. The ratio of the number of pions originated from Δ^0 resonance decay to the number of all pions (resonant and nonresonant) is estimated. The analogous ratio for protons is also determined.

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In relativistic nucleus-nucleus collisions an extended hot and dense fireball medium is created. During the expansion of the fireball, two freeze-out conditions are defined, chemical and thermal, representing the end of the inelastic and elastic interactions. Resonances with their short lifetime (few fm/*c*), and strong coupling to the dense and hot medium, have unique characteristics to probe various properties of this hot fireball. Depending on the medium conditions, energy density, temperature, and the degrees of freedom, various modifications to resonance properties, such as mass, width (lifetime), as well as the resonance yields and spectra, are expected [1–3]. Resonances with extremely short lifetimes enable us to directly measure these in-medium effects.

Additionally, in a dynamically evolving system, the produced resonances decay, and may be regenerated. The products of the resonances, decaying inside the medium, may also scatter on other particles from the medium (mostly pions). The rescattering and regeneration processes for resonances and their decay particles depend on the individual cross sections, and are dominant after the chemical freeze-out, but before the kinetic freeze-out. These interactions may result in changes of the reconstructed resonance yields, momentum spectra and widths [4–8]. Thus the measurement of resonance yields and their ratios to the corresponding stable particles, in nucleus-nucleus collisions and comparison to proton-proton collisions, facilitates an investigation of the dynamics from chemical to kinetic freeze-out. The comparison of resonances with different lifetimes, and different quark contents, may lead to information about the time evolution, density, and temperature during the expansion of the fireball medium. Experimental studies of the Δ^0 and Δ^{++} resonances via $(p, \pi^{\pm})$ correlations in collisions of light nuclei (He + C, C + C) at 4.2*A* GeV, and in heavy ion collisions (Ni + Ni, Au + Au, Ni + Cu) at energies between 1 and 2*A* GeV can be found in [9–12]. Also, the measurement of the Δ^{++} resonance in $p + p$ and d + Au collisions at $\sqrt{s_{NN}} = 200$ GeV using the STAR detector at RHIC is presented in [13].

Here we present a study of the $\Delta^0(1232) \rightarrow p\pi^-$ resonance production in peripheral C + Ta collisions at 4.2*A* GeV. The data were obtained using the 2-m propane bubble chamber exposed at JINR Dubna Synchrophasotron. To study the C + Ta collisions, three tantalum foils (1 mm thick) were placed inside the propane bubble chamber working in the 1.5 T magnetic field. The characteristics of the chamber allowed precise determination of the multiplicity and momentum of all charged particles, as well as identification of all negative particles. All recorded negative particles, except identified electrons, were taken to be π^-. Among them remained an admixture of unidentified fast electrons (<5%). All positive particles with momenta less than 0.5 GeV were classified either as protons or π^+ mesons according to their ionization density and range. Positive particles with momenta above 0.5 GeV were taken to be protons. Among them, the admixture of π^+ of approximately 7% was subtracted statistically. From the resulting number of protons, the projectile spectators (protons with momenta $p > 3$ GeV and emission angle $\theta < 4^{\circ}$) and target spectators (protons with momenta $p < 0.3$ GeV) were further subtracted. The remaining protons were denoted as participant protons, n_p. For this analysis a sample of 2000 C + Ta events was available with average number of negative pions and participant protons, $\langle n_{\pi^-} \rangle = 3.66 \pm 0.08$ and $\langle n_p \rangle = 14.3 \pm 0.3$, respectively.

To determine the mass distribution of Δ^0 resonances the invariant mass for each $p\pi^-$ pair in an event is calculated:

$$M_{p\pi} = \sqrt{(E_p + E_\pi)^2 - (\mathbf{p}_p + \mathbf{p}_\pi)^2},$$

where E_p, E_π, $\mathbf{p}_p$, $\mathbf{p}_\pi$ are energies and momenta of protons and pions, respectively. The resulting $p\pi^-$ invariant mass distributions for C + Ta events with number of participant protons $n_p < 10$ and $n_p < 15$, as well as for minimum bias events are shown in Fig. 1. Events with $n_p < 10$ and $n_p < 15$, correspond to peripheral collisions and represent ≈49%, and ≈62%, of the total inelastic cross section, respectively. The corresponding average multiplicities of negative pions and participant protons in these collisions are $\langle n_{\pi^-} \rangle = 1.10 \pm 0.04$ and $\langle n_p \rangle = 3.7 \pm 0.1$ for events with $n_p < 10$, and $\langle n_{\pi^-} \rangle = 1.63 \pm 0.05$ and $\langle n_p \rangle = 5.5 \pm 0.1$ for events with $n_p < 15$. From Fig. 1 one can see that in the peripheral collisions a peak for $n_p < 10$, or a shoulder for $n_p < 15$, can be observed above the background in the vicinity of the $\Delta^0(1232)$ resonance mass. This peak becomes wider with increasing n_p or increasing

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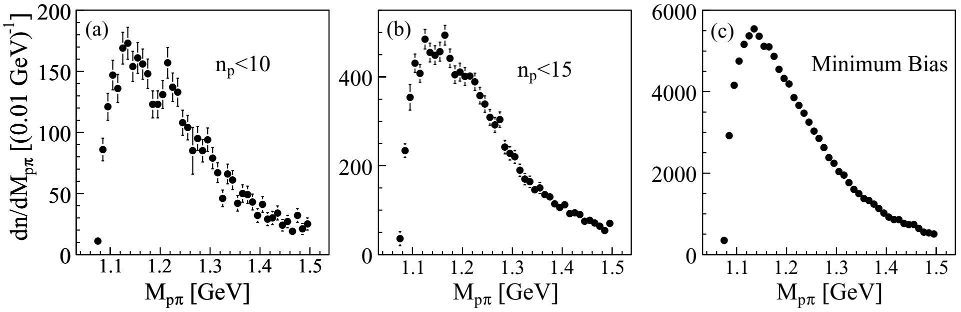

FIG. 1. The $p\pi^-$ invariant mass distributions for peripheral C + Ta events with number of participant protons $n_p < 10$, $n_p < 15$, and for minimum bias events.

collision centrality, due to increase of combinatorial background (which arises from non resonant combinations), and due to the rescattering of pions and protons. Consequently for higher centrality collisions and for inclusive C + Ta collisions, the resonance signal diminishes and becomes indistinguishable from the smooth background.

The shape of the background below the resonance signal, has a simple form and can be approximated with an analytic function. We find that an exponential background of the form

$$\frac{dn}{dM_{p\pi}} = A \exp\left(BM_{p\pi} + CM_{p\pi}^2\right),$$

where A, B, and C are constants to be determined, is sufficient to provide a good representation of the data everywhere except in the region just above the threshold.

In Fig. 2, the dashed line around Δ^0 mass and solid line outside Δ^0 mass region, represents the fit of data to this exponential background. By subtraction of exponential background from the experimental invariant mass distribution, the resulting raw distribution, shown in Fig. 3, is obtained. In order to estimate $\Delta^0(1232) \to p\pi^-$ resonance yield, and also mass and width, the raw distribution is fitted to the relativistic Breit-Wigner function [14]

$$F_{BW} = \frac{M_{p\pi} M_0 \Gamma}{\left(M_0^2 - M_{p\pi}^2\right)^2 + M_0^2 \Gamma^2},$$

where M_0 and Γ are the mass and width of the resonance. Following this procedure we obtained that in 974 peripheral C + Ta collisions with $n_p < 10$, about 116 $\Delta^0(1232) \to p\pi^-$ resonances are produced, corresponding to the average multiplicity of Δ^0 resonance, $\langle n_{\Delta^0} \rangle = 0.12 \pm 0.01$. Similarly we obtained that in 1233 C + Ta collisions with $n_p < 15$, about 170$\Delta^0(1232) \to p\pi^-$'s are produced, so that the corresponding average Δ^0 multiplicity is $\langle n_{\Delta^0} \rangle = 0.14 \pm 0.01$. The mass and width of Δ^0 resonance, that are obtained using this procedure are $M_{\Delta^0} = (1.226 \pm 0.004)$ GeV and $\Gamma = (0.025 \pm 0.009)$ GeV. The resulting fit of the invariant mass distribution to the relativistic Breit-Wigner plus exponential function for C + Ta collisions with $n_p < 10$ is displayed in Fig. 2.

The fitted value for the mass of Δ^0 resonance is practically not shifted toward lower values. However, Δ^0 resonance width that we obtain, is lower than that for the free hadron collisions. By fitting the resulting raw distribution displayed in Fig. 3, to the Breit-Wigner function, with and without momentum dependent width [14], we found that variation of the resonance width is smaller than 20%. Similarly, in He + C [9] and C + C collisions [10,15] at 4.2A GeV, it was found that for Δ^0, Δ^{++}, and the Roper resonance $N(1440)$, the extracted masses were not shifted toward lower values, while the widths were narrower than that corresponding to the average values [120 MeV for Δ and ≈350 MeV for $N(1440)$] [16]. For Δ^0 the extracted width was 103 ± 7 MeV (He + C) and 93 ± 8 MeV (C + C), while for Δ^{++} this width was 65 ± 5 MeV (He + C) and 85 ± 8 MeV (C + C). For the $N(1440)$ resonance the extracted width was 130 ± 20 MeV. The reduced widths of Δ^0 and Δ^{++} were also observed in peripheral heavy ion collisions [11].

It is of some interest to compare Δ^0 production with the production of negative pions and protons, and to estimate the fraction of the number of final state pions and protons arising from Δ^0 decays. The average multiplicity of Δ^0 resonances,

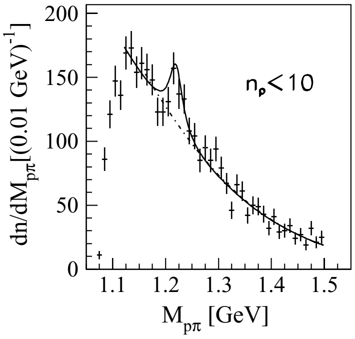

FIG. 2. The fit of the $p\pi^-$ invariant mass distribution to the exponential background (dashed line) plus relativistic Breit-Wigner function (solid line) for peripheral C + Ta collisions with $n_p < 10$.

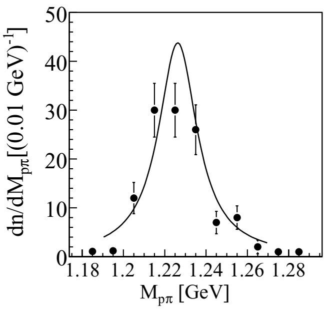

FIG. 3. The resulting raw distribution (dots) obtained by subtraction of the exponential background from the data, and the fit to the relativistic Breit-Wigner function (solid line) for peripheral C + Ta collisions with $n_p < 10$.

TABLE I. The average multiplicity and average kinematical characteristics of Δ^0 resonances, π^- and protons from Δ^0 resonance decay and all π^- and protons in peripheral C + Ta collisions with $n_p < 10$.

	$\langle n \rangle$	$\langle p_T \rangle$	$\langle y \rangle$
Δ^0	0.12 ± 0.01	0.487 ± 0.008	1.05 ± 0.02
Δ^0 (proton)		0.421 ± 0.007	1.08 ± 0.02
$\Delta^0(\pi^-)$		0.196 ± 0.003	1.09 ± 0.02
proton	3.7 ± 0.1	0.403 ± 0.007	0.87 ± 0.01
π^-	1.10 ± 0.04	0.226 ± 0.005	0.95 ± 0.02

and average multiplicities of negative pions and protons, in collisions with $n_p < 10$, are shown in Table I. It is seen that ≈11% of the final state negative pions and ≈3% of the final state protons originate from the Δ^0 decay ($\Delta^0/\pi^- = 0.11 \pm 0.01$ and $\Delta^0/\text{p} = 0.032 \pm 0.001$). These results are in fair agreement with predictions of the quark-gluon-string model (QGSM) [17]. According to this model, in peripheral C + Ta collisions, ≈14% of the number of all π^- mesons and ≈5.5% of the number of all protons arise from Δ^0 resonance decay. In total, in peripheral C + Ta collisions, 77% of all π^- and 27% of all protons originate from the decay of the lowest lying resonances (Δ, ρ, ω, η, η'), while the rest originate from the nonresonant primary and secondary interactions: $NN \to NN\pi$, $\Delta N \to \Delta N$, $\pi N \to \pi N$, $\pi NN \to NN$. Thus, while Δ^0 production and decay is a significant source of final state pions, other sources must contribute to the majority of the produced pions.

To obtain transverse momentum, p_T, and rapidity, y, distributions of Δ^0 resonances, one needs to have the $M_{p\pi}$ distributions for various intervals of p_T and y, in order to extract the number of Δ^0's in the manner described above. Since our statistics is insufficient to carry out this procedure, we select Δ^0 candidates using the angle between the outgoing proton and pion [10]. If Δ^0 resonance decays in flight, this angle, in the laboratory frame, is given by

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

where p_p, p_π are proton and pion momenta, E_p, E_π are their energies and $M_\Delta = 1232$ MeV is the mass of Δ resonance. This angle is compared to the experimentally measured angle between proton and pion momenta

$$\cos\beta = \frac{\mathbf{p}_p \cdot \mathbf{p}_\pi}{p_p p_\pi},$$

and only the combinations which satisfy the inequality

$$|\cos\beta - \cos\alpha| < \epsilon$$

are accepted. In this inequality, ϵ denotes an arbitrary cutoff parameter theoretically lying in the interval [0,2]. To decrease the contribution of uncorrelated pairs, we use $\epsilon = 0.22$, and additionally select only the $p\pi^-$ pairs from the interval (1.15–1.29) GeV. Clearly this distribution has a maximum at Δ^0 mass.

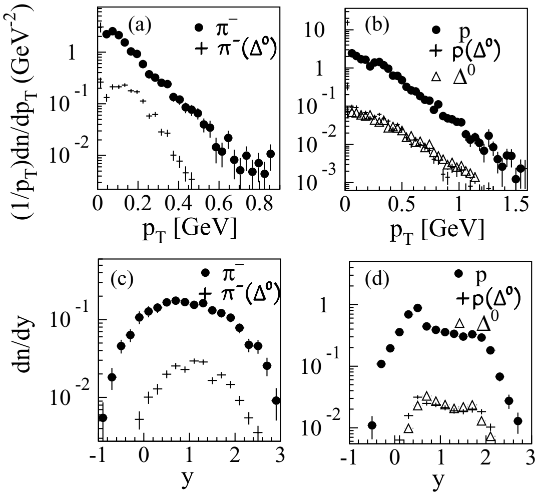

FIG. 4. Transverse momentum (top) and rapidity distributions (bottom) of Δ^0 resonances, π^-, and protons from Δ^0 resonance decay and all π^- and protons in peripheral C + Ta collisions with $n_p < 10$. All distributions are normalized to the corresponding average multiplicities.

The average kinematical characteristics of Δ^0 resonances, π^-, and protons from Δ^0 resonance decay, and all π^- and all protons (resonant and nonresonant), from C + Ta collisions with $n_p < 10$, are shown in Table I. The corresponding transverse momentum and rapidity distributions are compared in Fig. 4. It is seen that distributions of Δ^0 resonances are proton-like. At the same time, the p_T and rapidity distributions of reconstructed Δ^0 resonances and distributions of the protons from Δ^0 decay are practically the same. Comparison with the p_T distribution of all protons, shows that the Δ^0 resonances are produced with higher transverse momenta and that the corresponding $\langle p_T \rangle$ is higher ≈20%. The rapidity distribution of Δ^0 resonances has a two-peak shape. The two peaks (projectile-like and target-like) are almost symmetrical with respect to the nucleon-nucleon center-of-mass rapidity ($y_{\text{c.m.}} = 1.1$ for 4.2 GeV), and $\langle y \rangle$ is close to this value. The rapidity distribution of Δ^0 resonances occupies mainly the central rapidity region. The rapidity distribution of all protons has also a two-peak structure, although the target-like peak is more prominent, so that $\langle y \rangle$ is moved toward the target rapidity region. Contrary to the protons, the negative pions from Δ^0 decay are mainly produced in the low p_T region ($p_T < 0.5$ GeV), suggesting that Δ^0 decay kinematics is responsible for the low transverse momentum enhancement observed at the incident beam energies from 1 to 15A GeV [18–22]. The rapidity distribution of pions from Δ^0 decay has a Gaussian-like shape with maximum close to the nucleon-nucleon center-of-mass rapidity.

In conclusion, the production of $\Delta^0(1232) \to p\pi^-$ resonance is studied in C + Ta collisions at 4.2A GeV. In peripheral collisions a resonance signal in invariant $p\pi^-$ mass distribution is observed above a smooth background in the vicinity of the Δ^0 mass. It is found that Δ^0 mass is not shifted toward lower values, while the width of the resonance is narrower than the width corresponding to the average value. It is also found that the $\Delta^0(1232) \rightarrow p\pi^-$ resonances are produced in $\approx$12% of peripheral events, and that 11% of of π^- and 3% of protons originate from the Δ^0 decay. Analysis of kinematical characteristics of Δ^0 resonances shows that they are produced with higher transverse momenta in comparison to the proton distribution and that Δ^0 decay kinematics is responsible for the low transverse momentum enhancement of the negative pions.

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