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Investigation of Δ^0 and Δ^{++} isobar production in central p^{12}C and d^{12}C collisions at 4.2 A GeV/c

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Abstract

In this paper, we present experimental data on various characteristics of Δ^0 and Δ^{++} isobars produced in central p^{12}C and d^{12}C collisions at a beam momentum of 4.2 A GeV/c. The collision centrality is defined by the number of participating protons formed in the events under study. Experimental values of the mean multiplicity of participating protons are determined for both types of collisions. It is shown that, for p^{12}C and d^{12}C interactions, the effective masses and the widths of the mass spectra of the Δ^0 and Δ^{++} isobars coincide within experimental uncertainties. Furthermore, the average multiplicities of Δ^0 isobars are found to be larger than those of Δ^{++} isobars for both collision systems considered.

1 Introduction

The study of non-nucleonic degrees of freedom in nuclei is one of the fundamental problems of modern nuclear physics. Since the discovery of the proton–neutron structure of the nucleus [1, 2, 3], a long path has been traversed, encompassing the concepts of quasiparticles and pions, pion and baryon resonances, and, subsequently, partons, quarks, and gluons, as discussed in numerous scientific works and reviews. In this context, the production of baryon resonances, and in particular the Δ resonance, remains a topical subject of research for both experimental and theoretical studies.

This interest is motivated, first, by the fact that the Δ resonance can be produced universally in a wide range of strong and electromagnetic interactions involving pions, nucleons, nuclei, photons, and electrons. Second, a considerable amount of experimental data on Δ-resonance production exhibits nontrivial features, while existing theoretical models are unable to provide an unambiguous and comprehensive description of the full body of experimental results, especially for Δ production in the nuclear medium.

Experimental studies of Δ-resonance excitation in heavy-ion collisions [4, 5, 6, 7, 8] have demonstrated that both the mass and the width of the resonance differ significantly from those of the Δ resonance produced in free nucleon–nucleon interactions. This indicates a modification of hadronic properties in a dense nuclear medium formed in nucleus–nucleus collisions, leading to noticeable changes in the mass and width of the $\Delta(1232)$ resonance. Such effects have been interpreted within the framework of thermal and isobar models [1, 9].

At present, experimental data on the production of Δ^0 and Δ^{++} isobars in hadron–nucleus and nucleus–nucleus collisions at high energies remain rather limited, with only a few studies available, and even fewer devoted specifically to central collisions. Previous investigations of baryon resonances have shown that the mass width of the Δ^0 isobar is reduced by approximately 20–25% ($\Gamma = 85 - 95$ MeV) [10, 11, 12, 13, 14, 15] compared to the width $\Gamma \approx 120$ MeV observed for isobars produced in nucleon–nucleon or pion–nucleon collisions.

For the first time, the production of the Δ^0 resonance in n^{12}C collisions at a momentum of 4.2 A GeV/c was studied separately in the target and projectile fragmentation regions [16]. The mass width of the Δ^0 isobar produced in the target fragmentation region was found to be 47 ± 2 MeV, which is approximately 2.5 times smaller than the width of the Δ resonance produced in free nucleon–nucleon interactions. To explain this result, it was hypothesized that, inside the target nucleus, the nuclear potential inhibits the decay of the isobar until it leaves the region of the nuclear potential. In our subsequent work [17], it was argued that the lifetime of the Δ^0 isobar produced inside the target nucleus consists of two contributions: the time required to traverse the nucleus and the intrinsic decay time of a free Δ^0 isobar.

In view of the above considerations, a comparative study of Δ^0 and Δ^{++} resonance production in central p^{12}C and d^{12}C collisions at 4.2 A GeV/c, which constitutes the main objective of the present work, is of particular interest. Although the experimental data set has been employed in earlier publications, the novelty of the present analysis lies in the exclusive selection of central events and the simultaneous extraction and comparison of Δ^0 and Δ^{++} resonance signals under identical conditions.

2 Experimental Data Acquisition Method and Obtained Results

The present work is based on experimental data obtained with the 2-m propane bubble chamber of the Laboratory of High Energies (LHE), Joint Institute for Nuclear Research (JINR). The chamber was exposed to beams of protons and deuteron nuclei with a momentum of 4.2 GeV/ c per nucleon from the Dubna Synchrophasotron. The analyzed data sample consists of 6736 p^{12}C and 7071 d^{12}C events. The numbers of selected central events are 686, corresponding to $(10.2 \pm 0.4)\%$ for p^{12}C collisions, and 987, corresponding to $(14.0 \pm 0.4)\%$ for d^{12}C collisions.

Negative pions are identified visually solely by the sign of their electric charge. The admixture of unidentifiable electrons among negatively charged particles does not exceed 4%, while the contribution from strange negatively charged particles is below 1%. The lower momentum threshold above which charged pions can be reliably identified is 55 MeV/ c, whereas for protons this threshold is 140 MeV/ c. Protons and π^+ mesons are visually identified in the momentum region $p < 750$ MeV/ c.

A detailed description of the procedure used for the effective statistical separation of fast protons and π^+ mesons in the momentum region $p > 750$ MeV/ c, as well as the method for introducing corrections accounting for small losses of particles emitted at large angles with respect to the photographic plane, can be found in Refs. [11, 18, 19, 20]. In the present analysis, contributions to the momentum characteristics of secondary π^- mesons with track projection lengths shorter than 4 cm have also been taken into account. For such π^- mesons, only the emission angles could be measured, which makes a direct determination of their momenta impossible due to the limited track length within the sensitive volume of the chamber. The momentum reconstruction for these π^- mesons was performed as follows. Momentum spectra of π^- mesons with track projection lengths exceeding 4 cm were constructed and subdivided into 18 histograms according to their emission angle θ in the laboratory frame ($0^\circ \leq \theta \leq 180^\circ$), with an angular interval of $\Delta\theta = 10^\circ$. Then, for each π^- meson with a track projection length shorter than 4 cm, the momentum value was randomly sampled from the corresponding momentum histogram associated with its measured emission angle.

To identify Δ isobars in central collisions of the interactions under consideration, the procedure described in Ref. [10] was applied. For the decay of a Δ isobar in flight, the angle α between the outgoing proton and pion in the laboratory frame is determined by the relation

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

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

$$\cos\beta = \frac{\vec{p}_p \cdot \vec{p}_\pi}{p_p p_\pi}. \tag{2}$$

The experimental distribution dn/dM as a function of the invariant mass M of $p\pi$ pairs was constructed using the following selection criteria:

1. Only $p\pi$ combinations satisfying the inequality

$$|\cos\beta - \cos\alpha| < \varepsilon \tag{3}$$

were accepted, where ε is a cutoff parameter that theoretically lies in the interval $[0,\, 2]$. The more accurately the proton and pion momenta are measured, the smaller the upper limit of this interval should be.

2. In $d^{12}\mathrm{C}$ collisions at 4.2 A GeV/c per nucleon, protons with momenta $p > 3$ GeV/c and emission angles relative to the primary beam $\theta < 4^\circ$ were treated as spectator protons and excluded from further analysis.

3. Protons emitted from the carbon target with laboratory-frame momenta $p < 0.2$ GeV/c were regarded as evaporative and were also excluded from consideration.

It should be noted that among the criteria listed above, criterion (1) is the most effective, providing the strongest suppression of the combinatorial background.

The experimental invariant-mass distributions were obtained using the selection criteria described above by combining protons and pions within each individual event. The background distributions were constructed using the same selection criteria; however, in this case, protons and pions were combined randomly from different events. To account for the influence of event topology in the construction of the background distributions, only events with identical charged-particle multiplicities were mixed.

For each studied resonance, the number of generated background combinations exceeded the number of combinations in the corresponding experimental distribution by a factor of five or more. When comparing with the experimental spectra, the background distributions were normalized to the total number of combinations observed in the experiment. The resonance mass distribution was obtained by analyzing the difference between the experimental and background invariant-mass spectra according to the relation

$$D(M) = \frac{dn}{dM} - \alpha\,\frac{dn^b}{dM}, \tag{4}$$

where α is a normalization factor, dn/dM is the experimental invariant-mass distribution of π^-p or π^+p pairs, and dn^b/dM is the corresponding background invariant-mass distribution normalized to the total number of experimental combinations for the given pair type and collision system.

Interpreting the distribution $D(M)$ as a pure Δ-resonance signal, it was approximated by the relativistic Breit–Wigner function [21]

$$b(M) = \frac{M M_\Delta \Gamma}{\left(M^2 - M_\Delta^2\right)^2 + M_\Delta^2 \Gamma^2}, \tag{5}$$

where M_Δ and Γ denote the mass and the width of the resonance, respectively.

The set of $D(M)$ distributions obtained for various values of the parameters ε and α was fitted with the Breit–Wigner function $b(M)$, and the corresponding χ^2 values were calculated for each fit. The resonance parameters M_Δ and Γ were determined by minimizing the χ^2 value. Thus, for each experimental spectrum corresponding to a given choice of ε and α, a unique pair of parameters (M_Δ, Γ) was obtained. The optimal values of the parameters ε and α were determined from an analysis of the $\chi^2(\varepsilon, \alpha)$ dependence by locating the global minimum of the $\chi^2(\varepsilon, \alpha)$ function.

Protons attributed to target participants were defined as those with momenta in the interval $0.3 \le p \le 1.25$ GeV/c. The mean multiplicities of participant protons in p^{12}C and d^{12}C collisions were found to be 0.91 ± 0.01 and 1.12 ± 0.01, respectively. Since, in both collision systems, the average number of participant protons per interaction is close to unity, central collisions were defined as those p^{12}C and d^{12}C events in which the number of participant protons satisfies $N_p \ge 3$. This threshold, being significantly higher than the mean value, is intended to select events with small impact parameters, in which a substantial fraction of the projectile nucleons interacts with a dense region of the target nucleus. Such a definition of centrality is consistent with approaches commonly used in similar bubble-chamber experiments. We note that variations of this threshold (e.g., $N_p \ge 2$ or $N_p \ge 4$) lead to qualitatively similar results for the extracted Δ-resonance widths, while the chosen criterion provides an optimal compromise between event statistics and the purity of the central-collision sample.

Systematic uncertainties in the extracted resonance parameters originate from several sources, including particle identification (e.g., admixtures of electrons or kaons in the pion sample), the background construction procedure (dependence on the parameters ε and α), and the fitting procedure (choice of the invariant-mass fitting range). A dedicated analysis, in which these conditions were varied within reasonable limits, indicates that the systematic uncertainty in the extracted resonance mass M_Δ is of the order of $\pm(5-8)$ MeV, while the corresponding uncertainty in the width Γ amounts to $\pm(8-12)$ MeV. These values are comparable to the statistical uncertainties reported in the present work.

Figures 1 and 2 show the difference distributions between the experimental and background invariant-mass spectra for $\pi^- p$ and $\pi^+ p$ pairs in central p^{12}C and d^{12}C collisions at 4.2 GeV/c per nucleon. The optimal values of the parameters ε and α used in the analysis are indicated in the figure captions, while the solid curves represent fits obtained with the relativistic Breit–Wigner function. As seen from Figs. 1–4, the Breit–Wigner function provides a good description of the data for all considered reaction channels. In each case, a pronounced resonance-like structure is observed in the vicinity of $M \approx 1.23$ GeV, which is attributed to the production of the Δ^0 and Δ^{++} isobars.

The fitted curves reproduce well the shape of the experimental distributions over the entire invariant-mass range considered, including both the peak region and the tails, indicating that the applied background subtraction procedure and the chosen selection criteria effectively suppress combinatorial background. No significant systematic deviations between the data points and the fitted Breit–Wigner curves are observed within the statistical uncertainties, which supports the reliability of the extracted resonance parameters.

A comparison of the spectra obtained for p^{12}C and d^{12}C collisions shows that, within errors, the extracted masses and widths of the Δ resonances are similar for both collision systems. At the same time, differences in the overall normalization of the distributions reflect variations in the average multiplicities of the produced Δ isobars, which are sensitive to the collision system and centrality selection.

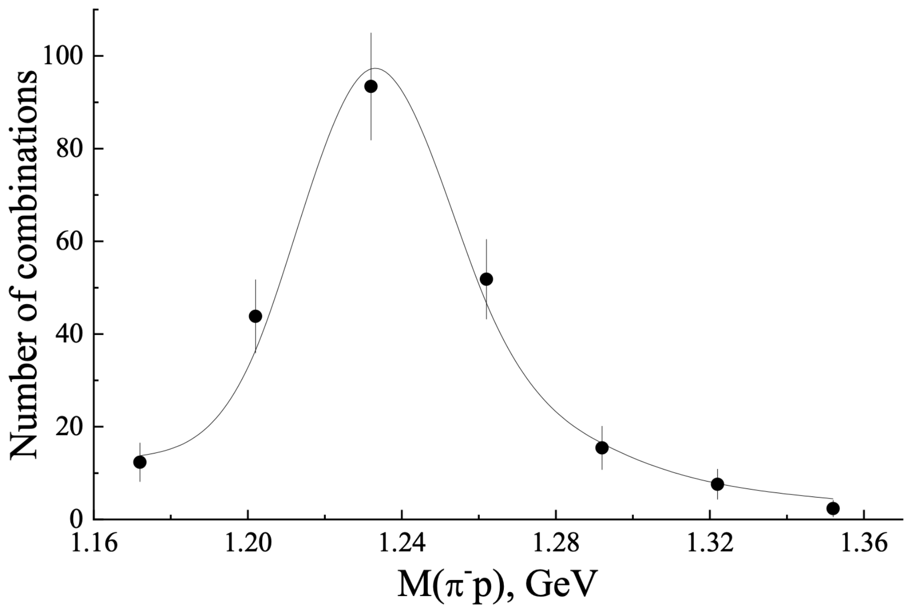

Figure 1: Distribution (•) of the difference between the experimental and background invariant-mass spectra for $\pi^- p$ pairs in central p^{12}C collisions at 4.2 A GeV/c. The parameters used in the analysis are $\varepsilon = 0.25 \pm 0.02$ and $\alpha = 0.40 \pm 0.02$. The solid curve represents the fit with the relativistic Breit–Wigner function.

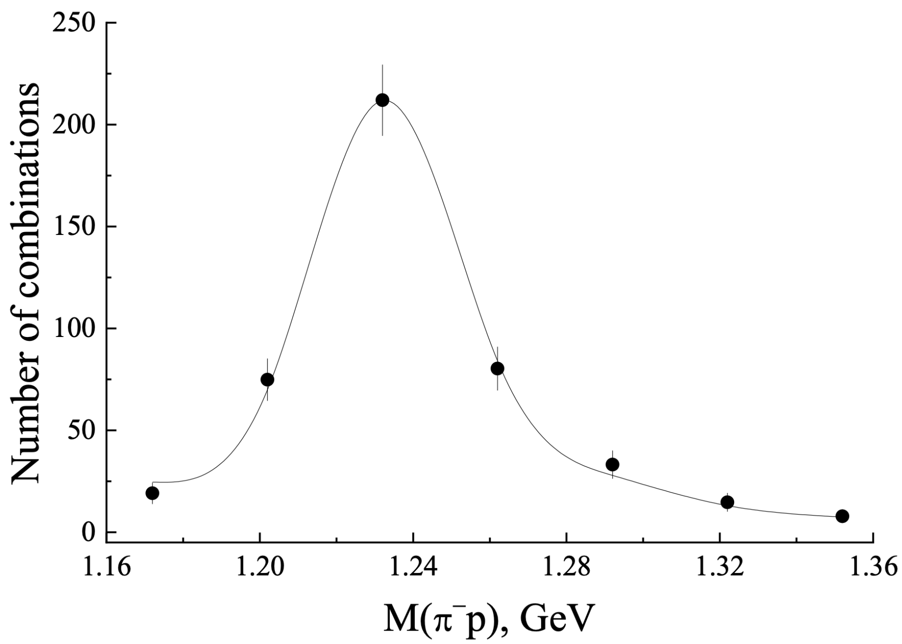

Figure 2: Distribution (•) of the difference between the experimental and background invariant-mass spectra for $\pi^- p$ pairs in central d^{12}C collisions at 4.2 GeV/c per nucleon. The parameters used in the analysis are $\varepsilon = 0.18 \pm 0.02$ and $\alpha = 0.13 \pm 0.02$. The solid curve represents the fit with the relativistic Breit–Wigner function.

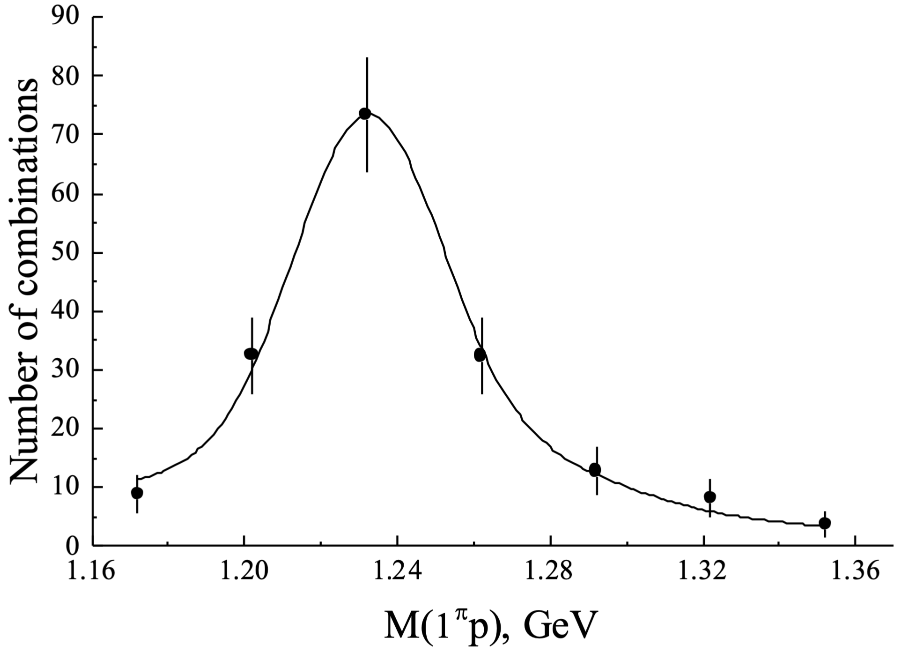

Figure 3: Distribution (•) of the difference between the experimental and background invariant-mass spectra for π^+p pairs in central p^{12}C collisions at 4.2 A GeV/c. The parameters used in the analysis are $\varepsilon = 0.30 \pm 0.02$ and $\alpha = 0.35 \pm 0.02$. The solid curve represents the fit with the relativistic Breit–Wigner function.

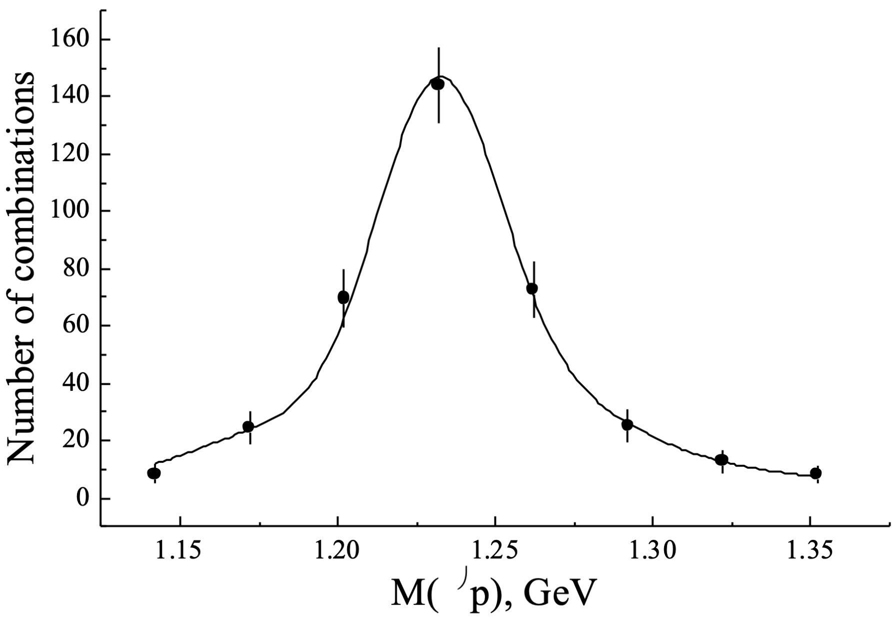

Figure 4: Distribution (•) of the difference between the experimental and background invariant-mass spectra for π^+p pairs in central d^{12}C collisions at 4.2 GeV/c per nucleon. The parameters used in the analysis are $\varepsilon = 0.30 \pm 0.02$ and $\alpha = 0.30 \pm 0.02$. The solid curve represents the fit with the relativistic Breit–Wigner function.

From the fits to the invariant-mass spectra presented in Figs. 1–4, the resonance masses M_Δ, widths Γ, and the average multiplicities of the Δ^0 and Δ^{++} isobars were extracted. The obtained values are summarized in Table 1 and serve as the basis for the quantitative comparison and discussion presented in the following section.

Table 1: Values of the mass M and mass-spectrum width Γ, as well as the average multiplicities of Δ^0 and Δ^{++} isobars produced in central p^{12}C and d^{12}C collisions at 4.2 GeV/c per nucleon.

Collision type	$M(\Delta^0)$, MeV	$M(\Delta^{++})$, MeV	$\Gamma(\Delta^0)$, MeV	$\Gamma(\Delta^{++})$, MeV	$\langle N_{\Delta^0} \rangle$	$\langle N_{\Delta^{++}} \rangle$
p^{12}C	1235 ± 3	1233 ± 3	51 ± 6	52 ± 6	0.36 ± 0.03	0.25 ± 0.02
d^{12}C	1234 ± 2	1233 ± 3	45 ± 4	54 ± 5	0.48 ± 0.03	0.37 ± 0.03

As can be seen from Table 1, within statistical uncertainties the extracted average masses and widths of the Δ resonances are consistent with each other for both collision systems. In contrast, for both p^{12}C and d^{12}C collisions, the average multiplicities of Δ^0 isobars are found to exceed those of Δ^{++} isobars.

This behavior can be understood from the constraints imposed by electric charge conservation. In events containing a positively charged pion, the average proton multiplicity is necessarily smaller than in events with a negatively charged pion. In addition, in p^{12}C collisions the average multiplicity of π^+ mesons exceeds that of π^- mesons, which can be attributed to charge-exchange processes of the projectile proton, leading to the production of a π^+ meson and a neutron. Although in d^{12}C collisions the average multiplicities of positive and negative pions are approximately equal, charge conservation still leads to a lower average proton multiplicity in events with a π^+ meson compared to those containing a π^- meson.

3 Conclusion

This work presents a dedicated analysis of Δ^0 and Δ^{++} isobar production in central p^{12}C and d^{12}C collisions at 4.2 GeV/c per nucleon. Within statistical uncertainties, the extracted masses and mass-spectrum widths of both resonances are found to be independent of the type of incident particle (proton or deuteron) and to coincide with each other. At the same time, for both collision systems the average multiplicities of Δ^0 isobars are observed to exceed those of Δ^{++} isobars, despite only a slight difference in the average number of participant protons.

A key result of the present study is that the mass-spectrum widths of the Δ resonances produced in central collisions are, on average, about 2.4 times smaller than the corresponding width of the Δ isobar produced in free nucleon–nucleon interactions. This pronounced narrowing is attributed to the influence of the dense nuclear medium formed in central collisions. While a simplified interpretation associates this effect with the constraining role of the nuclear potential, which delays the decay of the resonance inside the nucleus, the observed behavior is also consistent with more general concepts of in-medium modifications of hadron properties. These include effects related to collisional broadening, Pauli blocking, and modifications of the available phase space, as discussed within contemporary transport and in-medium theoretical models [22, 23]. The present results thus provide valuable experimental input for ongoing theoretical studies of baryon resonances in nuclear matter.

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