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Study of charged particle production in central pC and dC collisions at a beam momentum of 4.2 GeV/c per nucleon

R. Bekmirzaev[1,*], K. Olimov[2], M. Sultanov[3], B. Yuldashev[4,¶], S. Yuldashev[5], F. Tugalov[1], K. Mamatkulov[6]

[1]Jizzakh State Pedagogical University, Jizzakh, Uzbekistan

[2]Physical-Technical Institute, Academy of Sciences of Uzbekistan, Tashkent, Uzbekistan

[3]Samarkand State Architectural and Construction University, Samarkand, Uzbekistan

[4]Institute of Nuclear Physics, Academy of Sciences of Uzbekistan, Tashkent, Uzbekistan

[5]Samarkand State University, Samarkand, Uzbekistan

[6]Joint Institute for Nuclear Research, Dubna, Russia

e-mail: bekmirzaev@mail.ru

[¶]Deceased

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Abstract

This paper presents a systematic study of charged pion and proton production in inelastic p^{12}C and d^{12}C collisions at a beam momentum of 4.2 GeV/c per nucleon as a function of collision centrality, which is characterized by the net charge Q of secondary particles serving as an experimental estimator of the number of participating nucleons. We analyze the average multiplicities and kinematic characteristics of π^+, π^-, and protons, including the mean momentum $\langle p\rangle$, transverse momentum $\langle p_T\rangle$, emission angle $\langle\theta\rangle$, and rapidity $\langle y\rangle$. The experimental results are compared in detail with predictions of the FRITIOF model, which provides a satisfactory overall description of the particle multiplicities. A clear centrality dependence is observed: with increasing Q, the average momentum of pions decreases while their mean emission angle increases, indicating an enhanced role of secondary intranuclear interactions. These effects are more pronounced in pC than in dC collisions. The data presented in this work provide a quantitative benchmark for hadronic transport models in the few-GeV energy range.

1 Introduction

The interaction of high-energy nuclei with a target nucleus provides an effective tool for studying multi-nucleon collisions and the properties of nuclear matter under conditions of elevated density. In the energy range of a few GeV per nucleon, nuclear reactions are governed by a complex interplay between elementary nucleon–nucleon interactions, resonance production and decay, and secondary intranuclear scattering processes. Experimental studies in this regime therefore offer important insights into the transition from elementary hadronic processes to more complex nuclear dynamics.

A key aspect of such investigations is the classification of events according to their collision centrality, which is closely correlated with the impact parameter and, consequently, with the number of participating nucleons. In early studies of proton–nucleus and light nucleus–nucleus interactions, the multiplicity of participant protons or charged particles was frequently used as an experimental measure of centrality [1, 2, 3]. Although this approach does not provide a direct determination of the impact parameter, it allows for a practical event-by-event characterization of the collision geometry.

The production of charged pions and protons plays a central role in understanding reaction mechanisms at intermediate energies. Pions are predominantly produced through the excitation and decay of baryonic resonances and are therefore sensitive to both the initial nucleon–nucleon collisions and subsequent intranuclear interactions. Protons, on the other hand, carry information about nuclear stopping, energy dissipation, and the degree of participant–spectator separation. Systematic measurements of pion and proton observables as functions of collision centrality thus provide valuable constraints on theoretical models of hadronic and nuclear interactions.

While our collaboration has previously analyzed selected aspects of this experimental data set [4, 5], those studies were limited either to specific collision systems or to a restricted set of observables. In contrast, the present work offers a novel and systematic investigation with the following specific aims:

1. to perform a parallel and consistent analysis of p^{12}C and d^{12}C collisions using a unified centrality classifier based on the net charge Q;

2. to present, for the first time, the complete centrality dependence, from peripheral to central collisions, of differential kinematic observables, namely $\langle p\rangle$, $\langle p_T\rangle$, $\langle\langle\theta\rangle$, and $\langle y\rangle$, for identified π^+ and π^- mesons as well as participant protons in these light nuclear systems;

3. to carry out a detailed, observable-by-observable test of the FRITIOF model performance over the full centrality spectrum.

This approach enables a quantitative characterization of the transition in reaction dynamics from peripheral to central collisions and allows the relative importance of secondary intranuclear interactions to be assessed. In particular, a comparison between proton–carbon and deuteron–carbon systems provides insight into the role of projectile size and the number of interacting nucleons in shaping the final-state particle distributions.

In this work, the collision centrality is characterized by the experimentally constructed "net" charge Q, which serves as a proxy for the net charge of the participating nucleon system. For pC interactions, it is defined as

$$Q = n^+ - n^- - n_p^{\mathrm{eva}}, \tag{1}$$

where n^+ and n^- denote the numbers of positively and negatively charged singly charged particles, respectively, and n_p^{eva} is the number of evaporative protons emitted from the target nucleus with momentum $p < 0.2$ GeV/c.

For dC collisions, the definition of Q is extended to account for spectator nucleons:

$$Q = n^+ - n^- - n_p^{\mathrm{s}} - n_p^{\mathrm{t}}. \tag{2}$$

Here, n_p^{s} denotes spectator protons from the deuteron projectile with $3 \le p \le 5.4$ GeV/c and emission angle $\theta < 3^\circ$, while n_p^{t} represents slow spectator protons from the carbon target with $p < 0.3$ GeV/c. This observable allows events to be classified from peripheral (low $|Q|$) to central (high $|Q|$) collisions in a consistent manner for both collision systems.

2 Experimental Method and Data Analysis

The experimental data were obtained from exposures of the 2 m propane bubble chamber at the Laboratory of High Energies (LHE), Joint Institute for Nuclear Research (JINR), to proton and deuteron beams with a momentum of 4.2 GeV/c per nucleon. The bubble chamber was operated in a uniform magnetic field of 1.5 T. Detailed descriptions of the event selection procedure, visual scanning, track measurement, and applied corrections can be found in our previous publications [4, 5, 6, 7, 8].

Negative pions were identified visually by their negative charge. The admixture of unidentified electrons in the π^- sample does not exceed 4%, while the contamination from strange particles is below 1%. The lower momentum threshold for reliable pion identification was 55 MeV/c. Protons and π^+ mesons were visually identified for momenta $p < 750$ MeV/c. For higher momenta ($p > 750$ MeV/c), a statistical separation procedure was applied to distinguish protons from π^+ mesons [**?**, **?**].

For π^- mesons with very short track projections (shorter than 4 cm), the momentum reconstruction was performed using a statistical method based on the angular distributions of well-measured negative pions. This procedure allows a reliable extension of the pion sample to low momenta, which is essential for the study of centrality-dependent trends.

2.1 Systematic Uncertainties

The main sources of systematic uncertainty in the present analysis are the following:

1. *Particle identification:* uncertainties associated with the statistical separation of π^+ mesons and protons for $p > 750$ MeV/c, as well as the small admixture of electrons and kaons in the pion sample;

2. *Track reconstruction:* uncertainties related to efficiency corrections and momentum assignment for particles with short tracks, which are determined using a statistical reconstruction procedure;

3. *Centrality selection:* the dependence of the centrality parameter Q on the specific momentum and angular cuts used to define spectator and evaporative protons.

A dedicated analysis in which these selection criteria were varied within reasonable physical limits indicates that the resulting systematic uncertainties in the average multiplicities and kinematic observables are of the same order as, or smaller than, the statistical uncertainties quoted in this work. The main conclusions regarding the observed centrality-dependent trends are therefore robust with respect to these systematic effects. In addition, the same centrality definitions, kinematic cuts, and particle identification criteria were applied to both the experimental data and the FRITIOF model simulations. This ensures a consistent and unbiased comparison between measured observables and model predictions.

3 Theoretical Model: FRITIOF

The experimental results are compared with calculations performed using the FRITIOF model [9, 10, 6], a Monte Carlo approach based on the multiple scattering formalism and string dynamics. The model incorporates the Glauber framework to describe the geometry of nuclear collisions and treats nucleus–nucleus interactions as a superposition of successive elementary nucleon–nucleon collisions.

For the present analysis, we employed a version of the FRITIOF model adapted for beam energies down to approximately 4 GeV per nucleon, based on JINR Preprint No. P2–96–419 [9] and its subsequent implementations described in Refs. [6, 7, 8]. This version includes the Fermi motion of nucleons inside the colliding nuclei and explicitly accounts for the formation and decay of baryonic resonances, such as the Δ resonance, which play a dominant role in particle production at intermediate energies.

Within this framework, particle production proceeds via string excitation and fragmentation, followed by resonance decays. The model thus provides a baseline description of reaction dynamics in terms of sequential, largely independent nucleon–nucleon interactions. Explicit in-medium modifications of hadron properties and collective nuclear effects are not included, which defines the range of applicability of the model and should be taken into account when interpreting deviations between model predictions and experimental data.

Monte Carlo simulations were generated separately for pC and dC collisions. The simulated events were processed using exactly the same definitions of the centrality parameter Q, kinematic cuts, and particle selection criteria as those applied to the experimental data. This ensures a consistent and unbiased comparison between measured observables and FRITIOF model predictions.

4 Results

4.1 Multiplicities versus Centrality

The average multiplicities of charged pions and participant protons in pC and dC collisions, grouped into bins of the centrality parameter Q, are presented in Tables 1 and 2, respectively. The results are shown separately for the experimental data and for calculations performed with the FRITIOF model (denoted as FRT) to facilitate a direct comparison. The quoted uncertainties represent statistical errors only.

The centrality bins are chosen such that they span the full range from peripheral to central collisions and contain sufficient event statistics in each bin. This binning allows for a systematic investigation of the evolution of particle multiplicities with increasing centrality.

For both collision systems, the total charged-particle multiplicity increases monotonically with increasing Q, reflecting the growing number of participating nucleons in more central collisions. The multiplicities of π^+ and π^- mesons exhibit similar qualitative trends, while the absolute values and relative contributions depend on the projectile type. In particular, pC collisions show a pronounced excess of π^+ over π^- production, whereas in dC collisions the yields of positive and negative pions are nearly balanced, consistent with the isospin composition of the projectile.

The FRITIOF model reproduces the overall increase of pion and proton multiplicities with centrality reasonably well for both systems. Deviations between the model predictions and the experimental data become more visible in the most central bins, especially for the multiplicities of participant protons, indicating possible limitations of the model in the description of secondary intranuclear interactions at high centrality.

For pC collisions, peripheral interactions ($Q \leq 2$) constitute a large fraction (above 70%) of the total inelastic cross section. The average multiplicity of π^+ mesons significantly exceeds that of π^- mesons, which is a characteristic feature of proton–nucleus interactions. By comparing the measured pion yields with those from proton–nucleon collisions at the same energy per nucleon, we estimate that approximately 30–40% of the produced pions originate from secondary intranuclear collisions within the carbon target.

In dC collisions, the average multiplicities of positive and negative pions are nearly equal for the full event sample (see the “all events” column in Table 2), which is consistent with the charge symmetry of both the deuteron projectile and the ^{12}C target. The FRITIOF model reproduces the overall multiplicity trends and their dependence on the centrality parameter Q reasonably well for both collision systems. However, the model tends to slightly overestimate the number of participant protons, particularly in more central collisions.

4.2 Kinematic Observables versus Centrality

The dependence of kinematic observables on collision centrality was investigated for π^+, π^- mesons, and participant protons. For both light nuclear systems, pC and dC, a clear and statistically significant trend is observed: with increasing values of the centrality parameter Q, corresponding to a transition from peripheral to more central collisions, the average momentum $\langle p \rangle$ of produced pions decreases, while their mean emission angle $\langle \theta \rangle$ increases. For example, in pC collisions, the mean pion momentum $\langle p_\pi \rangle$ decreases by approximately 30% between the most peripheral and the most central centrality bins.

This behavior is consistent with an increasing contribution from secondary intranuclear interactions. As the number of participating nucleons grows, produced particles undergo rescattering inside the nuclear medium, which leads to a softening of the momentum spectra and to more isotropic angular distributions.

Table 1: Average multiplicities in p^{12}C collisions at a beam momentum of 4.2 GeV/c per nucleon.

Q	1	2	3	4	5	6	all events
N_{ev}, exp.	1968	2816	1325	452	135	38	6736
FRT	28457	37635	16675	9551	5166	2516	100000
$\langle n_{\pm} \rangle$, exp.	2.73 ± 0.01	3.16 ± 0.02	4.69 ± 0.04	5.73 ± 0.07	6.72 ± 0.12	7.60 ± 0.20	3.61 ± 0.02
FRT	2.15 ± 0.01	2.93 ± 0.01	4.59 ± 0.01	6.01 ± 0.02	6.97 ± 0.02	7.71 ± 0.03	3.63 ± 0.01
$\langle n_{\pi^-} \rangle$, exp.	0.52 ± 0.01	0.32 ± 0.01	0.42 ± 0.02	0.48 ± 0.03	0.43 ± 0.05	0.36 ± 0.07	0.41 ± 0.01
FRT	0.48 ± 0.00	0.32 ± 0.00	0.42 ± 0.01	0.45 ± 0.01	0.45 ± 0.01	0.46 ± 0.01	0.41 ± 0.00
$\langle n_{\pi^+} \rangle$, exp.	0.42 ± 0.01	0.66 ± 0.01	0.96 ± 0.02	1.22 ± 0.04	1.40 ± 0.08	1.58 ± 0.16	0.71 ± 0.01
FRT	0.38 ± 0.00	0.66 ± 0.00	0.79 ± 0.01	0.87 ± 0.01	0.89 ± 0.01	0.93 ± 0.02	0.64 ± 0.00
$\langle n_p^{par} \rangle$, exp.	1.05 ± 0.02	1.74 ± 0.01	2.53 ± 0.02	3.22 ± 0.04	4.02 ± 0.09	5.10 ± 0.18	1.86 ± 0.01
FRT	1.09 ± 0.01	1.66 ± 0.00	2.62 ± 0.01	3.54 ± 0.01	4.46 ± 0.02	5.75 ± 0.03	2.08 ± 0.01

Table 2: Average multiplicities in d^{12}C collisions at 4.2 GeV/c per nucleon.

Q	1	2	3	4	5	6	7	all events
N_{ev}, exp.	1864	2124	1474	886	452	206	65	7071
FRT	2684	2836	1821	1292	798	442	127	10000
$\langle n_{\pm} \rangle$, exp.	1.43 ± 0.01	2.32 ± 0.05	3.53 ± 0.06	5.01 ± 0.03	6.02 ± 0.02	7.20 ± 0.02	8.43 ± 0.01	3.36 ± 0.02
FRT	1.46 ± 0.01	2.39 ± 0.05	3.64 ± 0.06	5.21 ± 0.03	6.14 ± 0.02	7.60 ± 0.02	8.65 ± 0.01	3.48 ± 0.02
$\langle n_{\pi^-} \rangle$, exp.	0.49 ± 0.02	0.50 ± 0.02	0.85 ± 0.01	0.91 ± 0.01	1.11 ± 0.01	1.21 ± 0.01	1.39 ± 0.01	0.63 ± 0.01
FRT	0.52 ± 0.02	0.58 ± 0.02	0.94 ± 0.01	0.99 ± 0.01	1.20 ± 0.01	1.33 ± 0.01	1.47 ± 0.01	0.69 ± 0.01
$\langle n_{\pi^+} \rangle$, exp.	0.55 ± 0.02	0.58 ± 0.02	1.61 ± 0.02	1.88 ± 0.01	2.09 ± 0.01	2.15 ± 0.01	2.26 ± 0.01	0.64 ± 0.01
FRT	0.58 ± 0.02	0.62 ± 0.02	1.68 ± 0.02	1.97 ± 0.01	2.18 ± 0.01	2.38 ± 0.01	2.38 ± 0.01	0.74 ± 0.01
$\langle n_p^{par} \rangle$, exp.	0.32 ± 0.02	0.83 ± 0.01	1.39 ± 0.01	2.01 ± 0.01	2.56 ± 0.01	2.99 ± 0.01	3.90 ± 0.01	1.12 ± 0.01
FRT	0.38 ± 0.02	0.93 ± 0.01	1.44 ± 0.01	2.09 ± 0.01	2.64 ± 0.01	3.12 ± 0.01	3.96 ± 0.01	1.19 ± 0.01

In contrast, the average transverse momentum $\langle p_T \rangle$ exhibits a much weaker dependence on centrality. Only a moderate increase of the order of 10% is observed for π^+ mesons with increasing Q. This indicates that the centrality-driven softening of the pion spectra occurs predominantly in the longitudinal direction, while the transverse momentum is largely governed by the underlying elementary production mechanisms.

The role of secondary interactions decreases with increasing projectile mass. This effect is reflected in the significantly weaker Q-dependence of $\langle p \rangle$ observed in dC collisions compared to pC interactions. The FRITIOF model reproduces the qualitative trend of decreasing $\langle p \rangle$ with increasing Q for both systems. However, for pions produced in central pC collisions, the model tends to underestimate the magnitude of the observed momentum softening, pointing to limitations in its treatment of secondary intranuclear processes.

The difference in the centrality dependence of the average multiplicities $\langle n_{\pi^+} \rangle$ and $\langle n_{\pi^-} \rangle$ in dC collisions can be understood in terms of elementary nucleon–nucleon interaction cross sections. At the considered energy, the reaction channel $pp \to pn\pi^+$ has a significantly larger cross section than $pn \to pp\pi^-$. In a deuteron projectile, the neutron can interact independently with the target nucleons, which enhances π^+ production via quasi-pp interactions as the number of participating nucleons increases, i.e., at higher values of Q.

5 Conclusion

In this work, we have presented a comprehensive experimental study of p^{12}C and d^{12}C collisions at a beam momentum of 4.2 GeV/c per nucleon, focusing on the dependence of charged-particle production on collision centrality characterized by the net charge Q.

The main conclusions can be summarized as follows:

1. The FRITIOF model provides a satisfactory overall description of the average charged-particle multiplicities over the full centrality range for both light nuclear systems, supporting its basic approach to the modeling of multiple nucleon–nucleon collisions.

2. Clear signatures of secondary intranuclear interactions are observed. With increasing centrality, the average momentum of produced pions decreases, while their mean emission angle increases. These effects are most pronounced in proton–carbon collisions.

3. The centrality dependence of kinematic observables is significantly weaker in deuteron–carbon collisions. This behavior indicates a transition in the dominant reaction mechanisms with increasing projectile size and number of participating nucleons.

4. The systematic data on particle multiplicities and differential kinematic observables presented in this study provide a valuable quantitative benchmark for the development and refinement of hadronic transport and string-based models in the intermediate-energy regime of a few GeV per nucleon.

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