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Dependence of average characteristics of π^- mesons on number of interacting protons in nucleus-nucleus collisions at 4.2 GeV/c per nucleon

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A 2-m propane bubble chamber was used to study pion production in interactions of light nuclei d,α, C with carbon at 4.2 GeV/c per nucleon. The average numbers of participant protons and correlated numbers of participant nucleons were estimated by using the net charge of secondaries. The dependence of the average values of multiplicity, momentum, and angular characteristics of π^- mesons on the number of interacting protons is also studied. The predictions of the Dubna version of the cascade model were found to be in qualitative agreement with results of this analysis.

I. INTRODUCTION

Extensive studies of relativistic nucleus-nucleus collisions have been undertaken in recent years. Such collisions can provide a unique source of dense, highly excited nuclear matter necessary for the appearance of exotic phenomena such as nuclear collective effects, pion condensates, or quark-matter production.[1–11] Although nothing really exotic has been found at available projectile energies experimental data are very helpful in improving our present understanding of hadronic-matter behavior in high-energy nuclear collisions. Particularly, the study of pion production may also shed some light on less exotic but equally important questions such as multiple scattering, testing of nuclear-transparency, thermalization processes, and constraining of model predictions. The knowledge of the number of interacting nucleons in the nucleus is fundamental for some of these tasks. As a measure of that number the net charge Q, defined as the difference between interacting positive particles and negative particles, may be used.

By using the net charge in the present analysis we determine the average number of interacting protons and correlated number of interacting nucleons in collisions of light nuclei d,α,C with carbon at a projectile momentum of 4.2 GeV/c per nucleon. The dependences of the average values of multiplicity, momentum, and angular characteristics of π^- mesons on the number of interacting protons are also studied for different incident nuclei. Experimental results are quantitatively compared with predictions of the Dubna version of the cascade-evaporation model (DCM). The model describes the simultaneous development of intranuclear cascades in both colliding nuclei. It takes into account the processes of production and pion absorption, depletion of the nuclear matter in the course of the intranuclear cascade, the Pauli principle, and effects of the relativistic contraction. The model is presented in detail in Ref. 12.

Multiplicity, momentum, and angular characteristics of π^- mesons produced in inelastic (d,α,C)C interactions have been reported previously.[13]

II. EXPERIMENTAL DATA

Experimental data have been obtained using the 2-m propane bubble chamber placed in a magnetic field of 1.5 T and exposed to beams of p, d, α, and C nuclei from the synchrophasotron (JINR, Dubna) with a momentum of 4.2 GeV/c per nucleon.

Interactions with propane in a fiducial volume inside the chamber were scanned, measured, and reconstructed by the GEOFIT program.

Interactions with carbon nuclei were selected from all interactions of beam nuclei with propane (C_3H_8) by using criteria based on the determination of the total charge of secondary particles, the number of protons, the presence of protons emitted backward, etc. This method, described in detail in Ref. 14 allows one to select 70–80% of all inelastic interactions of a given nucleus A with C. The A-C interactions, not satisfying the selection criteria, were collected together with inelastic A-p interactions to form a group of ambiguous events $(N_{Ap}^{\mathrm{in}}+N_{AC}^{\mathrm{in}})$ and were separated only statistically. The analysis is based on 4700, 1900, and 3300 inelastic dC, αC, and CC interactions.

In each event the number of secondary tracks was determined and a classification of the tracks was made according to the relative ionization and charge. All negative particles, except identified electrons, were considered as π^- mesons. The contamination by misidentified electrons and negative strange particles does not exceed 5% and 1%, respectively.[15] By ionization density and range positively charged particles were classified as π^+ mesons, protons, and spectators. Fragments with momentum $P_l/Z > 3$ GeV/c and emission angle $\theta_l < 4°$ were taken as spectators.[16] Spectators were separated as single charged (S_1), and those with charge $Z > 2$ (S_2). The multiplicities of secondaries were denoted as n_{π^-}, n_{π^+}, n_p, n_{S_1}, and n_{S_2}, respectively.

The propane-bubble-chamber technique has some experimental limitations. Protons, deuterons, and tritium nuclei with momenta less than 150, 250, and 350 MeV/c, respectively, are not seen in the chamber due to their short range in propane ($R < 3$ mm). Negatively charged pions with momenta of $P_{\pi^-} < 70$ MeV/c ($l < 3$ cm) can be wrongly classified as protons. Positively charged pions are undoubtedly identified by ionization only for momenta of $P_{\pi^+} < 600$ MeV/c. The number of π^+ mesons, as evaluated from the procedure described in Ref. 17, did not exceed 15% of the total number of positively charged particles with $P_+ > 0.5$ GeV/c. Among all positive particles with a momentum of $P > 1$ GeV/c and emission angle of $\theta_l > 4°$ about 1% had the ionization density greater than that of protons with the same momentum. These particles were classified as composite fragments without subdivision into deuterium, tritium, and helium nuclei.

III. EXPERIMENTAL RESULTS

A. The average number of interacting nucleons

Independent of the nature of the object colliding with nucleons inside the nucleus, it appears as either an extra positive charge when colliding with a proton, or no extra charge when colliding with a neutron. Thus one should observe an excess of positive charge which measures the number of interacting protons inside the nucleus.

In nucleus-nucleus interactions the excess of positive charge, from interacting nucleons, may be defined as

$$Q = n_+ - n_- - (n_p^f + n_t^f) ,$$

where n_+ (n_-) is the multiplicity of positive (negative) charged particles, n_p^f is the number of leading fragments traveling with the projectile velocity in a 4° forward cone, and n_t^f is the number of target fragments with $p_l < 300$ MeV/c.

TABLE I. Average numbers $\langle Q \rangle$ and dispersions D_Q of participant protons in (d,α,C)C interactions. The values of $\langle Q \rangle^{\rm DCM}$ are calculated according to DCM.

	dC	αC	CC
$\langle Q \rangle$	1.89±0.03	2.90±0.04	4.32±0.07
D_Q	1.30±0.02	1.78±0.02	2.88±0.04
$\langle Q \rangle^{\rm DCM}$	1.9	2.8	4.2

TABLE II. Average numbers of participant projectile $\langle N_p \rangle$ and target $\langle N_t \rangle$ nucleons and their summed value $\langle N \rangle$.

	dC	αC	CC
$\langle N \rangle$	3.78±0.06	5.80±0.08	8.64±0.14
$\langle N_p \rangle$	1.3 ±0.1	2.5 ±0.1	4.3 ±0.1
$\langle N_t \rangle$	2.5 ±0.1	3.3 ±0.1	4.3 ±0.1

Since the interactions of deuterons, helium, and carbon nuclei with a carbon satisfy isotopic symmetry, we expect that $\langle n_{\pi^+} \rangle$ and $\langle n_{\pi^-} \rangle$ are the same. Therefore the resultant $\langle Q \rangle$ is taken as the number of participant protons, assuming that all participants are singly charged.

The average numbers of participant protons in interactions of light nuclei d,α,C with carbon are given in Table I. The same table also gives the average numbers of participant protons obtained from DCM with experimental conditions taken into account.

If colliding nuclei have the same number of protons and neutrons, the average number of interacting nucleons $\langle N \rangle$ equals $2\langle Q \rangle$. Table II presents $\langle N \rangle$ for different projectile nuclei.

The number of interacting nucleons from a projectile nucleus $\langle N_p \rangle$ can be determined by counting the noninteracting (spectator) nucleons, as done previously in Ref. 13 for d and α projectiles. Knowing $\langle N \rangle$ and $\langle N_p \rangle$ the number of interacting nucleons from the target nucleus $\langle N_t \rangle$ is determined by subtracting the number of interacting nucleons from the projectile from the total number of interacting nucleons. For CC interactions there are some difficulties in the experimental estimation of $\langle N_p \rangle$ connected with the problems in the identification of fragments with $Z \geq 2$ from the C projectile.[18] For these interactions we suppose that $\langle N_p \rangle = \langle N_t \rangle = \langle N \rangle / 2$. The obtained values of $\langle N_p \rangle$ and $\langle N_t \rangle$ are presented in Table II.

For the sake of comparison with experimental values, the numbers of interacting nucleons from the projectile and the target were calculated by using the relations[19,20]

$$\langle \nu_p \rangle = A \sigma_{pB}^{\rm in} / \sigma_{AB}^{\rm in} , \qquad (1)$$

$$\langle \nu_t \rangle = B \sigma_{pA}^{\rm in} / \sigma_{AB}^{\rm in} . \qquad (2)$$

In these relations A and B are the mass numbers of the projectile and the target and $\sigma_{pB}^{\rm in}$, $\sigma_{pA}^{\rm in}$, and $\sigma_{AB}^{\rm in}$ are the inelastic cross sections for proton-nucleus and nucleus-nucleus collisions taken from Ref. 21. These relations are obtained from the independent collision model assuming that nucleons from the projectile interact with the target independently. Table III shows calculated values of $\langle \nu_p \rangle$ and $\langle \nu_t \rangle$. Knowing the mean number of interacting nucleons from the projectile and target (Table II) and having calculated values of $\langle \nu_p \rangle$ and $\langle \nu_t \rangle$ (Table III) one can

TABLE III. Average numbers of interacting projectile $\langle \nu_p \rangle$ and target $\langle \nu_t \rangle$ nucleons calculated from formulas (1) and (2).

	dC	αC	CC
$\langle \nu_p \rangle$	1.33	2.36	3.83
$\langle \nu_t \rangle$	2.21	2.72	3.83

deduce how many nucleons on average come from secondary processes (i.e., cascading) in the projectile and target nucleus:

$$\langle N_p \rangle_{\text{cascade}} = \langle N_p \rangle - \langle \nu_p \rangle$$

and

$$\langle N_t \rangle_{\text{cascade}} = \langle N_t \rangle - \langle \nu_t \rangle \ .$$

One can notice that cascading effects are negligible in d and α nuclei. From the mean number of interacting nucleons in the carbon nucleus approximately 14% are due to secondary collisions in the intranuclear cascade.

B. Dependence of pion multiplicity on the number of interacting protons

In nucleus-nucleus interactions the net charge varies between $0 \le Q \le Z_A + Z_B$, so, it is possible to distinguish different types of interactions in which Q protons participate from the projectile and target, while the number of interacting neutrons may fluctuate between 0 and n_A (n_B). At the same time one can expect these fluctuations to be damped because of similar space density distributions of protons and neutrons, particularly in light nuclei. In the $0 \le Q \le 1$ region multiple interactions on neutrons dominate. Interactions with two or more participating protons from the projectile and target give contributions in the $Q \ge 2$ region. As an example, Fig. 1 shows several possible types of interactions with $Q = 2$.

We also investigated the properties of this net charge. Besides the protons, π^+ mesons from $p \to n\pi^+$ may also contribute to Q in the final state of interactions with $Q \ge 2$. In the case when $\langle n_{\pi^+}(Q) \rangle = \langle n_{\pi^-}(Q) \rangle$ only protons give a contribution to Q. However, selecting the interactions with two or more participating protons one favors multiplicity of π^+ mesons over π^- mesons. The reason for this is that at our energies multiplicity of π^+ mesons produced in pp interactions is considerably higher than in nn interactions. From the isospin symmetry of pp and nn systems it follows that $\langle n_{\pi^+} \rangle_{pp} = \langle n_{\pi^-} \rangle_{nn}$. Interactions of protons with neutrons give on the average the same number of $\langle n_{\pi^+} \rangle$ and $\langle n_{\pi^-} \rangle$ mesons.

Figure 2 shows $\langle n_{\pi^+}(Q) \rangle$ and $\langle n_{\pi^-}(Q) \rangle$ vs Q in $(d,\alpha,\text{C})\text{C}$ interactions. One can see that in CC interactions there is a region $3 \le Q \le 10$ where $\langle n_{\pi^+}(Q) \rangle = \langle n_{\pi^-}(Q) \rangle$ [Fig. 2(a)]. For $3 \le Q \le 10$ this equality is also valid for π^+ mesons in the range 0.1—0.5 GeV/c, where π^+ mesons can be readily identified by ionization. It suggests that in the region $3 \le Q \le 10$ the number of interacting protons is approximately equal to the number of interacting neutrons. When asymmetry between colliding nuclei increases, the region of Q becomes narrower and the difference between $\langle n_{\pi^+}(Q) \rangle$ and $\langle n_{\pi^-}(Q) \rangle$ becomes greater [Figs. 2(b) and 2(c)].

The dependence of the average value of π^- multiplicity on Q is shown in Fig. 3 for various projectiles. In order to point out the effect of various projectile nuclei the same dependence is also shown for pC interactions. The following can be seen.

For interactions with $Q \ge 2$, the mean multiplicity increases linearly with Q, reaching a plateau at $Q \ge 2\langle Q \rangle$. The region of linear dependence increases with the projectile mass number. So, in CC interactions there is almost a

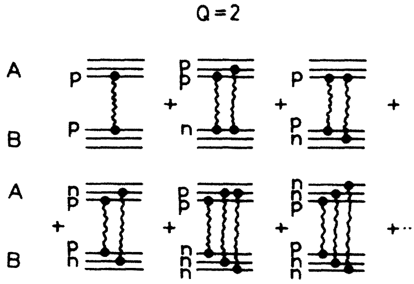

FIG. 1. Several possible types of multiple nucleon-nucleon interactions in nucleus-nucleus collisions with $Q = 2$.

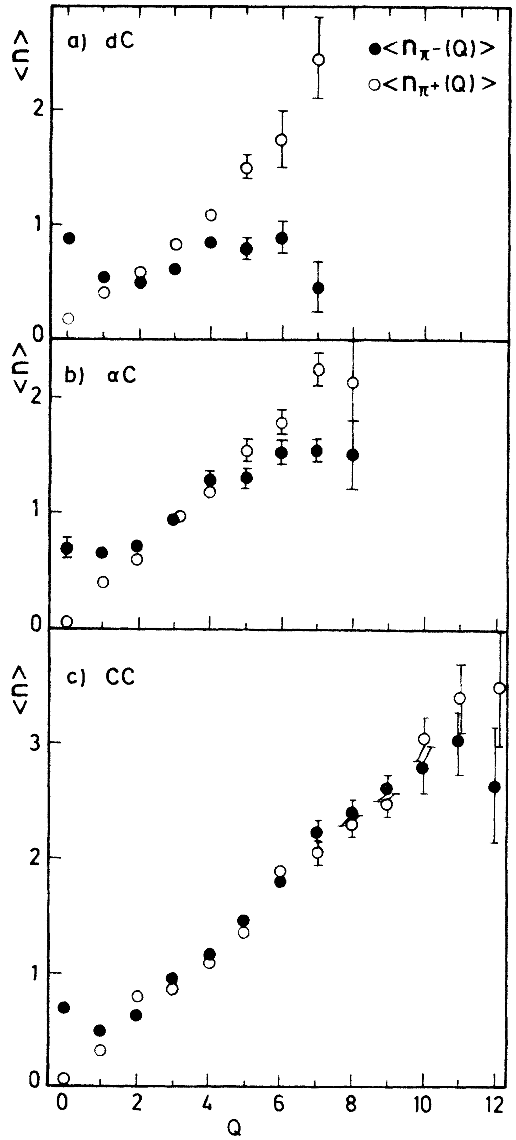

FIG. 2. The dependence of $\langle n_{\pi^-}(Q) \rangle$ and $\langle n_{\pi^+}(Q) \rangle$ on Q in dC, αC, and CC interactions.

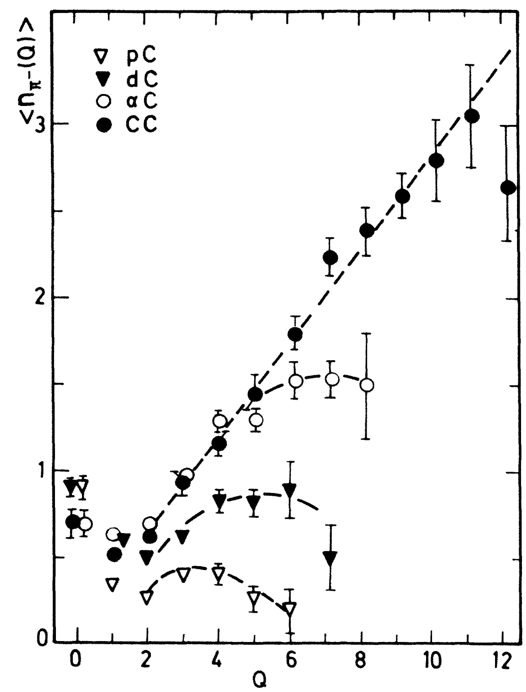

FIG. 3. Average multiplicity of π^- mesons as a function of Q for (p,d,α,C) interactions. Curves are to guide the eye.

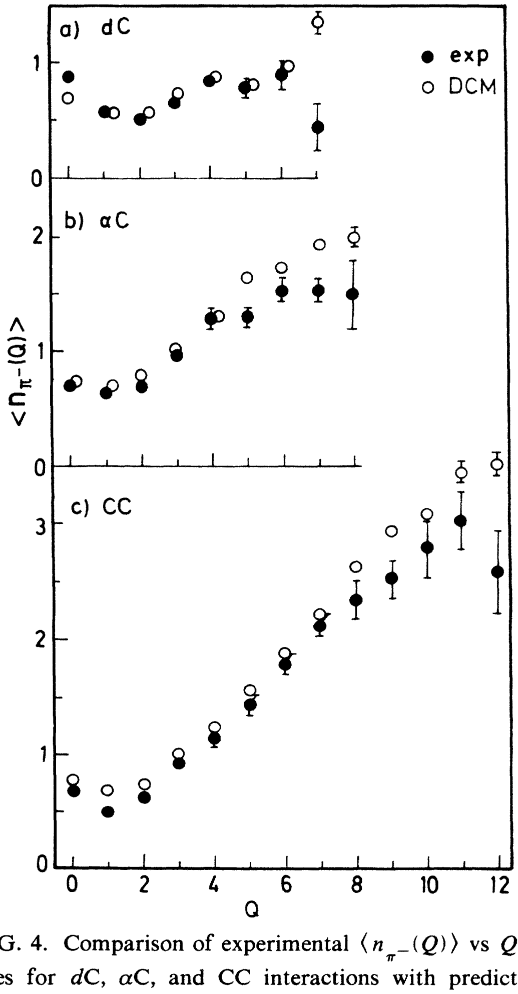

FIG. 4. Comparison of experimental $\langle n_{\pi^-}(Q)\rangle$ vs Q dependences for dC, αC, and CC interactions with predictions of DCM.

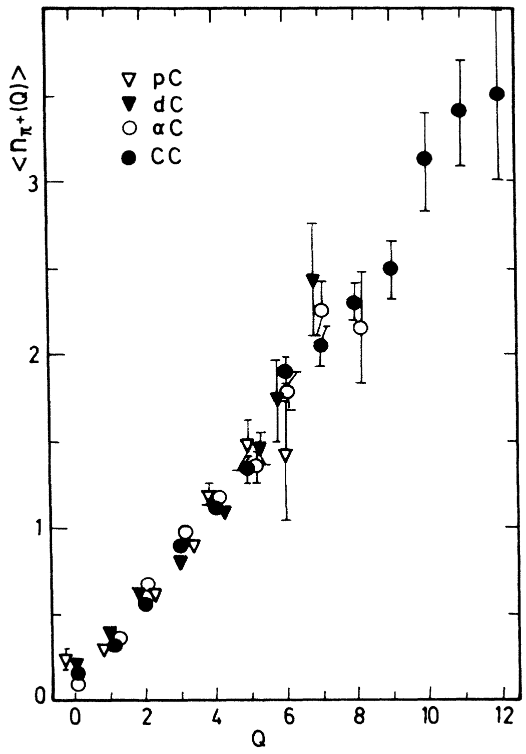

FIG. 5. Average multiplicity of π^+ mesons as a function of Q for $(p,d,\alpha,\mathrm{C})\mathrm{C}$ interactions.

linear dependence between $\langle n_{\pi^-}(Q)\rangle$ and Q. Linear dependence is also observed for equal-mass collisions, such as Ar + KCl at $E = 1.8$ GeV per nucleon.[22]

For each Q, $\langle n_{\pi^-}(Q)\rangle$ increases with the mass number of the projectile. That can be qualitatively explained by increase of the number of interacting nucleons from the projectile.

The dependence of $\langle n_{\pi^-}(Q)\rangle$ on Q is compared with the predictions of the DCM (Fig. 4). DCM correctly reproduces $\langle n_{\pi^-}(Q)\rangle$ vs Q dependence, for all three types of interactions although it slightly overestimates values of $\langle n_{\pi^-}(Q)\rangle$ at very high Q.

Mean multiplicities of π^+ mesons versus Q in $(p,d,\alpha,\mathrm{C})\mathrm{C}$ interactions are plotted in Fig. 5. Contrary to the case of π^- mesons, all experimental points of π^+ mesons are well described by one straight line independent of the incident nuclei. For all three types of interactions there is also a linear dependence between $\langle n_{\pi^+}(Q)\rangle$ and Q for π^+ mesons in the momentum range 0.1—0.5 GeV/c.

C. Dependence of the average kinematic characteristics of π^- mesons on the number of interacting protons

From the previous investigations[13] of inelastic $(d,\alpha,\mathrm{C})\mathrm{C}$ interactions it follows that increase of projectile mass number (from 2 to 12) causes little change in the shape of kinematic distributions and that the mean values of the kinematic variables do not change by more than 10%.

The dependences of momentum, rapidity, transverse

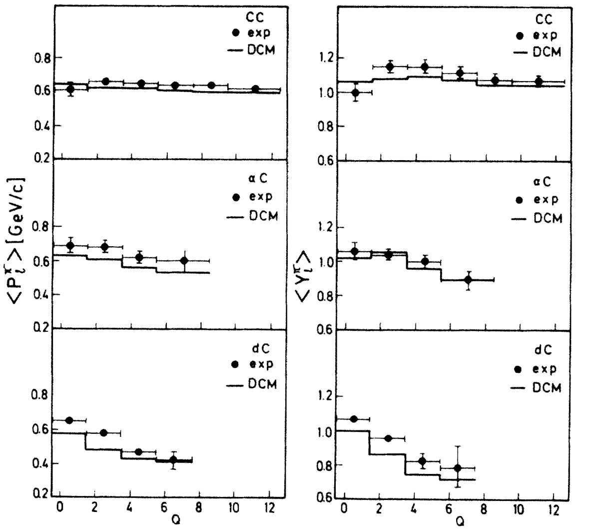

FIG. 6. Average momentum and average rapidity of π^- mesons as a function of Q in dC, αC, and CC interactions. The lines represent DCM calculations.

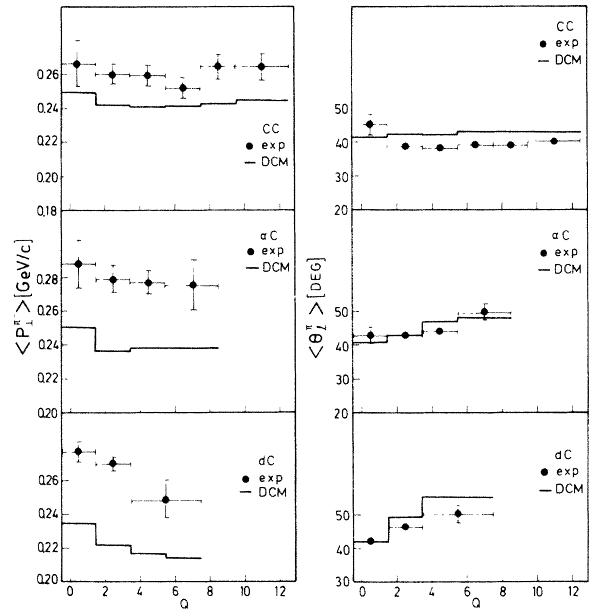

FIG. 7. Average transverse momentum and average emission angle of π^- mesons as a function of Q in (d,α,C)C interactions. The lines represent DCM calculations.

momentum, and emission angle of π^- mesons produced in inelastic (d,α,C)C interactions on the number of interacting protons are shown in Figs. 6 and 7. For interactions with two or more participating protons, $Q \geq 2$, characteristics of the dependences are the following.

In dC and αC interactions the average values of momentum rapidity and transverse momentum decrease with increasing Q. In the same time the mean angle of π^- emission increases with Q. The change of average values of kinematic variables with Q is more expressed going from αC to dC interactions.

In CC interactions $\langle P_l^{\pi^-} \rangle$, $\langle Y_l^{\pi^-} \rangle$, $\langle P_\perp^{\pi^-} \rangle$, and $\langle \theta_l^{\pi^-} \rangle$ do not depend on the number of interacting protons. For each Q within two statistical errors mean rapidity is compatible with $\langle Y_l^{\pi^-} \rangle = 1.1$ which corresponds to the value of the NN center-of-mass rapidity $Y_{NN}^{\text{c.m.}}$ for 4.2 GeV/c per nucleon.

The solid lines in the Figs. 6 and 7 represent DCM calculations. For all three types of interactions the model qualitatively reproduces the dependence of the average kinematic characteristics of π^- mesons on Q. However there is some difference between experimental values and DCM calculations. The worst agreement is obtained in the dependence of $\langle P_\perp^{\pi^-} \rangle$ on Q. This difference becomes smaller with the increasing mass number of the projectile.

IV. CONCLUSIONS

We have studied pion production in dC, αC, and CC inelastic interactions at 4.2 GeV/c per nucleon using a propane bubble chamber. Introducing the net charge we have determined the average number of participating protons and correlated number of participating nucleons. It was estimated that approximately 14% of the mean number of interacting nucleons in carbon nucleus were due to secondary collisions in the intranuclear cascade.

Multiplicity, momentum, and angular characteristics of π^- mesons were analyzed in terms of the number of interacting protons.

The following has been found.

In symmetric CC collisions the average multiplicity of π^- mesons increases linearly with the number of interacting protons. Average values of kinematic variables $\langle P_l^{\pi^-} \rangle$, $\langle Y_l^{\pi^-} \rangle$, $\langle P_\perp^{\pi^-} \rangle$, and $\langle \theta_l^{\pi^-} \rangle$ do not depend on Q.

In αC and dC collisions, $\langle n_{\pi^-}(Q) \rangle$ increases linearly with Q reaching a plateau at $Q \geq 2\langle Q \rangle$. Average values of $\langle P_l^{\pi^-} \rangle$,$\langle Y_l^{\pi^-} \rangle$,$\langle P_\perp^{\pi^-} \rangle$ decrease and $\langle \theta_l^{\pi^-} \rangle$ increases with increasing Q. The change of average kinematic characteristics with Q is more expressed going from αC to dC interactions.

The Dubna version of the cascade model qualitatively reproduces the studied dependences although there are some differences between experimental values and DCM calculations. The worst agreement is obtained in the dependence $\langle P_\perp^{\pi^-} \rangle$ on Q. This difference becomes smaller with the increasing mass number of the projectile.

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