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# Influence of collision centrality upon participant protons in d+C, $\alpha$+C, and C+C interactions at 4.2 GeV/*c* per nucleon

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The influence of collision centrality upon mean kinematic characteristics and spectra of participant protons d+C, $\alpha$+C, and C+C interactions at 4.2 GeV/*c* per nucleon is analyzed. The net charge $Q$ of secondary particles is used as a measure of collision centrality. An increase in $\langle p_T \rangle$ of participant protons with increasing $Q$ is observed for all types of interactions analyzed. The net charge is also seen to affect the form of the rapidity spectra of participant protons in C-C interactions. The intranuclear cascade model cannot explain the dependence of these proton characteristics upon $Q$.

## INTRODUCTION

High energy nucleus-nucleus collisions can be used to study the properties of nuclear matter at extremely high temperatures and densities. Under these conditions novel, exotic forms of hadronic matter may appear. For the experimentalist, the problem is then to recognize and extract these new phenomena from the obtained data. One way this can be done is by searching for significant deviations from that which is predicted by theoretical models which describe basic reaction mechanisms. It is therefore necessary to collect data on particle emission for various masses of interacting nuclei and beam energies. These basic reaction mechanisms can also be studied using data from fixed reactions in which impact parameters are varied.

Net charge $Q$ of secondary particles can be used to separate nuclear collisions with various impact parameters of "centrality." In nucleus-nucleus collisions this index of centrality is defined as

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

where $n_+$ and $n_-$ are the multiplicity of positively and negatively charged particles, respectively; $n_p^f$ is the number of leading fragments traveling at the projectile velocity in a 4° forward cone and $n_t^f$ is the number of target fragments with $p \leq 300$ MeV/*c*. The resultant $Q$ is the number of participant protons from the projectile and target nuclei. By using net charge the average number of participant protons in the nucleus-nucleus collisions has been previously determined.[1-3] The dependence of average negative pion multiplicity on the number of participant protons has also been investigated for various nuclei over the Bevelac and Dubna energy range.[1-4] In symmetric nuclear collisions a linear dependence of $\langle n_{\pi^-} \rangle$ upon the number of participant protons and the c.m. energy has been found.[1,2,4] The dependence of mean kinematic characteristics of $\pi^-$ mesons on the number of participant protons has been studied, as well, in d + C, $\alpha$+C, and C + C [(d,$\alpha$,C)C] interactions at 4.2 GeV/*c* per nucleon.[2] In C-C interactions the mean kinematic characteristics of $\pi^-$ mesons do not depend on the number of interacting protons.

In this work we continue[2] to examine the dependence of mean kinematic characteristics and spectra of participant protons in (d,$\alpha$,C)C interactions at 4.2 GeV/*c* per nucleon upon $Q$. Multiplicities and various inclusive distributions of all protons in (d,$\alpha$,C)C collisions are studied in the paper by Armutlisky *et al.*[5] Experimental results are compared with calculations made on the basis of the Dubna intranuclear cascade model.[6] In that model inelastic nucleus-nucleus interactions are treated as a superposition of successive quasi-free two-particle collisions described by the relativistic Boltzmann equation. Pion production and absorption, depletion of nuclear matter during the intranuclear cascade, the Pauli principle, and relativistic contraction are all taken into account. The time evolution of the system of interacting nuclei is simulated by the Monte Carlo technique. Approximations of the existing experimental data are used for the cross sections and other features of elastic and inelastic hadron-hadron collisions. Consequently, final states with an arbitrary number of particles are taken into account with the constraints imposed by conservation laws.

Using the cascade model, 17 000 d-C, 11 500 $\alpha$-C, and

13 000 C-C inelastic events at 4.2 GeV/$c$ per nucleon were generated and recorded on magnetic tape. Comparison with experimental results has shown that the cascade model satisfactorily reproduces multiplicities and the full inclusive spectra of $\pi^-$ mesons and protons.[5,7] In this paper we seek to determine whether the cascade model is capable of describing the characteristics of participant protons in collisions with various impact parameters.

## EXPERIMENTAL PROCEDURE

The data were obtained by exposing a 2-m propane bubble chamber to d, $^4$He, and $^{12}$C nuclear beams at an incident momentum of 4.2 GeV/$c$ per nucleon from the Dubna synchrophasotron. Since the chamber was filled with propane, the primary d-C, $\alpha$-C, and C-C interactions were not isolated directly. Instead, the procedure suggested in Ref. 8 was employed. By using criteria such as the total charge of secondary particles, the number of protons, the presence of back emitted protons, etc., 70% to 80% of all inelastic (d,$\alpha$,C)C interactions were separated. The (d,$\alpha$,C)C events not satisfying the selection criteria (and considered to be peripheral) were grouped with inelastic (d,$\alpha$,C)p interactions. These peripheral (d,$\alpha$,C)C events were then extracted by a statistical method based on known cross sections for (d,$\alpha$,C)C and (d,$\alpha$,C)p interactions. This method is applicable only if the distributions in the unseparated (d,$\alpha$,C)C events are assumed to be equivalent to corresponding distributions for the entire group of [(d,$\alpha$,$C$)C+(d,$\alpha$,C)p] events. The present analysis is based on 4700 d-C, 2000 $\alpha$-C, and 3200 C-C inelastic events.

Identification, classification, and measurement of all secondary particles is considered in more detail in Ref. 9. Here, attention will be primarily paid to protons. The bubble chamber allows a good $\pi^+$/p discrimination using ionization density and range in the momentum interval of 150-500 MeV/$c$. Protons with momenta of $p < 150$ MeV/$c$ are not seen in the chamber due to their short range in propane $R < 2$ mm. Among protons with a momentum of $p > 500$ MeV/$c$, there is a $\pi^+$ meson admixture which distorts the rapidity distribution. This defect can be corrected for isoscalar nuclear collisions, when the spectra for negative and positive pions are assumed to be equal. The number of protons is then obtained by subtracting the number of $\pi^+$ mesons with momentum $p < 500$ MeV/$c$ and the number of $\pi^-$ mesons with $p > 500$ MeV/$c$ from the total number of positive particles with $Z = 1$, i.e.,

$$n_{\rm p} = n^+_{z=1} - n_{\pi^+}(p < 0.5) - n_{\pi^-}(p > 0.5) \ .$$

It has thereby been estimated that the $\pi^+$ meson admixture among protons is less than 10%.

The bubble chamber technique does not allow the deuteron, tritium, and helium admixture to be eliminated from the protons. Therefore, all positively charged barions (including composite fragments) will be termed protons. According to various estimates, the d, t, and $^4$He admixture accounts for less than 10–15 % of all singly charged fragments.[10–12]

For each event protons are classified as either participants or as projectile or target spectators. Projectile spectators are protons and heavier fragments with momentum of $p/Z > 3$ GeV/$c$ and emission angle $\theta_l < 4°$. Target spectators are protons with $p < 300$ MeV/$c$. All spectators are weakly correlated with multiparticle production and are not considered in this paper. Protons with momenta of $p > 0.3$ GeV/$c$ and without projectile spectators are classified as participants.

The experimental conditions of registration and identification were applied to events generated by the cascade model. All neutral particles were excluded, as well as p, d, t, and $^3$He with momentum less than 150, 275, 350, and 525 MeV/$c$, respectively. Proton mass and momentum were assigned to deuterons with momentum from 275 to 800 MeV/$c$. t, $^3$He, and d with momentum greater than 350, 525, and 800 MeV/$c$, respectively, were all considered as protons, without recalculating momentum.

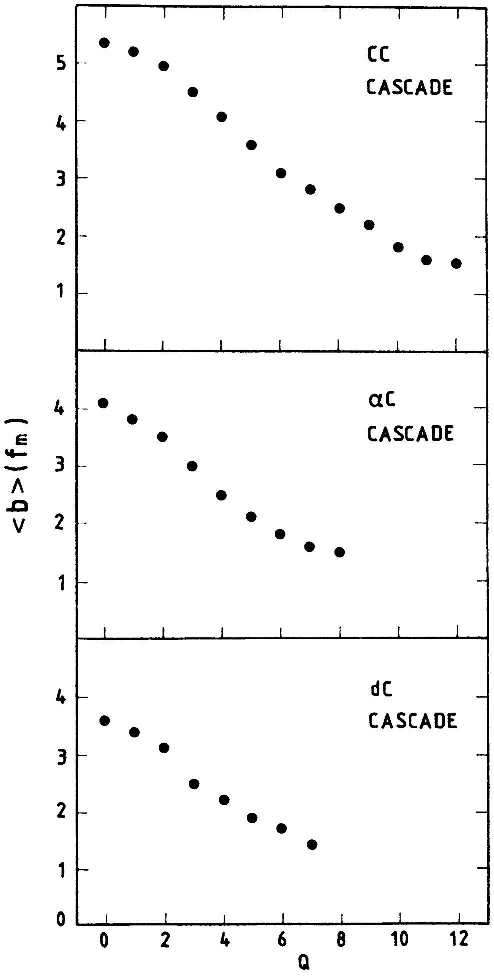

FIG. 1. Average impact parameter values plotted against $Q$ for d-C, $\alpha$-C and C-C interactions.

## DEPENDENCE OF MEAN VALUES OF KINEMATIC VARIABLES OF PARTICIPANT PROTONS ON $Q$

Using net charge, which in nucleus-nucleus collisions ranges from $0 \leq Q \leq Z_A + Z_B$, interactions are classified according to the number of participating protons, while the number of neutrons may fluctuate between 0 and $N_A$ ($N_B$). These fluctuations are expected to be damped because protons and neutrons have similar space density distributions, particularly in light nuclei. Multiple neutron interactions dominate at $Q=0$ and $Q=1$, whereas at $Q \geq 2$ multiple proton interactions are primary. Thus, by selecting interactions with $Q=2,3,\ldots,Z_A+Z_B$, processes with various impact parameter $b$ for each $Q$ value can be studied. This claim can be tested by the cascade model. In Fig. 1 the average impact parameter values are plotted against variable $Q$. In order to provide sufficient statistics, events are grouped as follows: $Q=0\text{-}1, 2\text{-}3, \ldots, Q_{\text{max}}$. There is a strong correlation between the average impact parameter value and $Q$, so that each dependence on $Q$ can be translated into dependence on the $\langle b \rangle$ value.

The relation between $Q$ and the average values of kinematic variables of participant protons is shown in Figs. 2 and 3. For interactions with two or more participating protons, this dependence can be described as follows. In the case of asymmetric systems of colliding nuclei (d-C and $\alpha$-C interactions) the average momentum and rapidity of participating protons decrease with increasing $Q$. At the same time, average transverse momentum and emission angle both increase with $Q$. In collisions of symmetric nuclear pair (C-C interactions), $\langle p \rangle$, $\langle y \rangle$, and $\langle \theta_l \rangle$ are independent of $Q$, while the average transverse momentum increases by 15±2 %.

In comparing mean values of kinematic variables for $\pi^-$ mesons[2] and participant protons, it is seen that $\langle p \rangle$, $\langle y \rangle$, and $\langle \theta_l \rangle$ show the same dependence upon $Q$. However, for protons, in contrast to $\pi^-$ mesons, the average transverse momentum increases from 3% to 15%, depending on the projectile nucleus. The average transverse momentum of $\Lambda$ hyperons also increases with $Q$.[13]

The experimental data and the cascade model calculations are compared in Figs. 2 and 3. For all three types of interactions, the model qualitatively reproduces the dependence of $\langle p \rangle$, $\langle y \rangle$, and $\langle \theta_l \rangle$ on $Q$, although there are some differences between the experimental values and

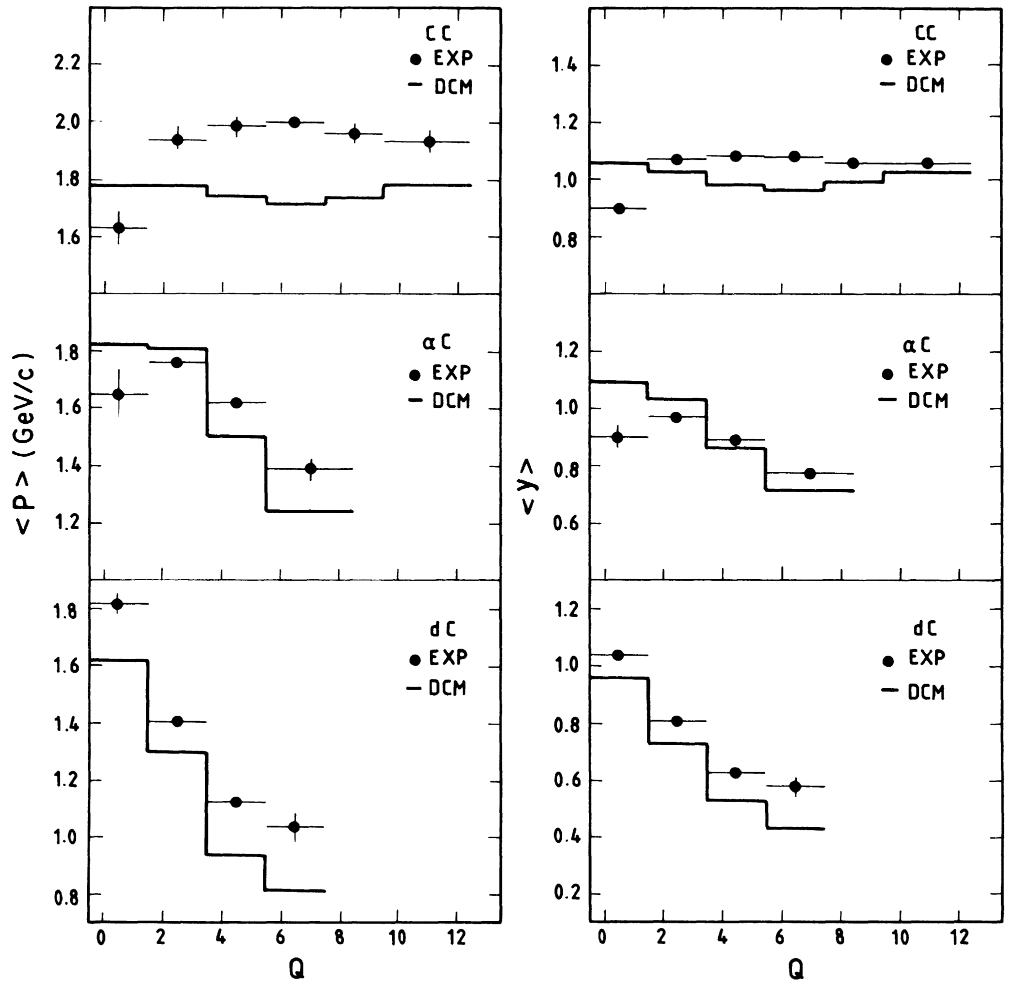

FIG. 2. The average momentum and average rapidity of participant protons as a function of $Q$ in d-C, $\alpha$-C, and C-C interactions. The solid lines correspond to cascade model calculations.

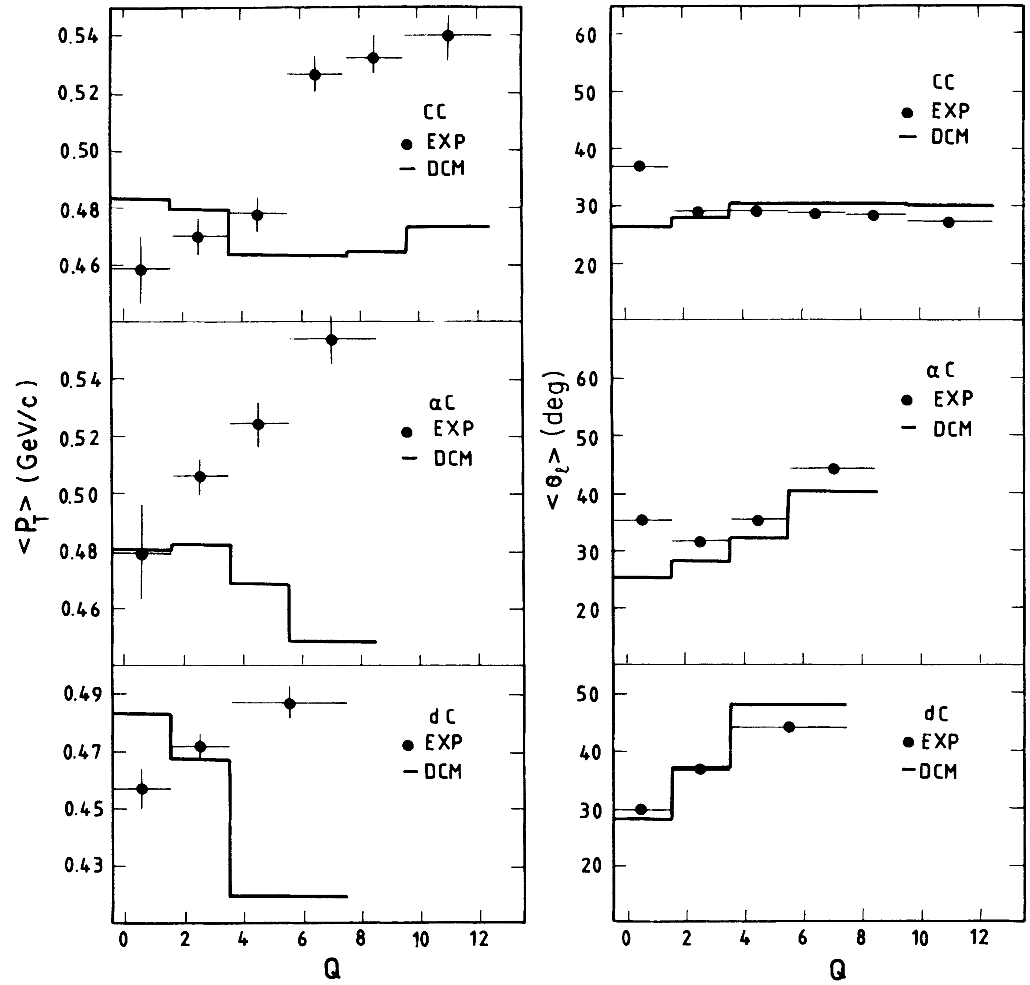

FIG. 3. Average transverse momentum and average emission angle of participant protons as a function of $Q$ in (d,$\alpha$,C)C interactions. The solid lines represent cascade model calculations.

those calculated from the model. However, the model does not even qualitatively describe the dependence of $\langle p_T \rangle$ on $Q$.

## DEPENDENCE OF PARTICIPANT PROTONS SPECTRA ON $Q$

Characteristics of participant protons in nucleus-nucleus collisions can be more completely determined by studying the dependence upon $Q$ of rapidity, transverse momentum, and other proton spectra. Rapidity is defined as

$$y = 0.5 \ln[(E + p_L)/(E - p_L)] ,$$

with $E$ and $p_L$ being energy and longitudinal momentum, respectively. At a projectile nucleus momentum of 4.2 GeV/$c$ per nucleon, the rapidity gap between target and projectile nuclei, $\Delta y = y(\text{proj}) - y(\text{tar})$ is 2.23, and the rapidity of the NN center of mass $y_{\text{c.m.}}$, is 1.1.

Figures 4(a) and 5(a) illustrate changes in proton rapidity distributions as a function of $Q$. The multiplication ratio

$$R(y) = (d\langle n \rangle/dy)_Q / (d\langle n \rangle/dy)_{Q=2-3}$$

is shown on the upper part of Figs. 4(a) and 5(a). By this ratio rapidity distributions for the maximum $Q$ are normalized by using those for $Q = 2$-3, where peripheral collisions predominate. When $A_t > A_p$ (Fig. 4), the proton multiplicity is higher in the back hemisphere ($y < y_{\text{c.m.}}$) and increases with $Q$. Consequently, the ratio $R(y)$ increases with decreasing $y$. The ratio $R(y)$ is less than one for maximum $y$, in the projectile fragmentation region. In collisions of nuclei of equal mass (Fig. 5), with increasing $Q$, proton multiplicity increases along the entire rapidity region, such that the $y$ distribution remains symmetric in relation to $y = y_{\text{c.m.}}$. For smaller $Q$ the proton multiplicity augments uniformly, while for the maximum $Q$ this growth is more pronounced in the central region $y = y_{\text{c.m.}}$. This loss of uniformity causes the form of the $y$ spectra to change with increasing $Q$. For $2 \le Q \le 7$ the contributions from projectile and target region are separable, and the distributions are bimodal, with a minimum at $y = y_{\text{c.m.}}$. For $Q \ge 8$ the contributions from the two fragmentation regions are not separable and the bimodal form disappears.

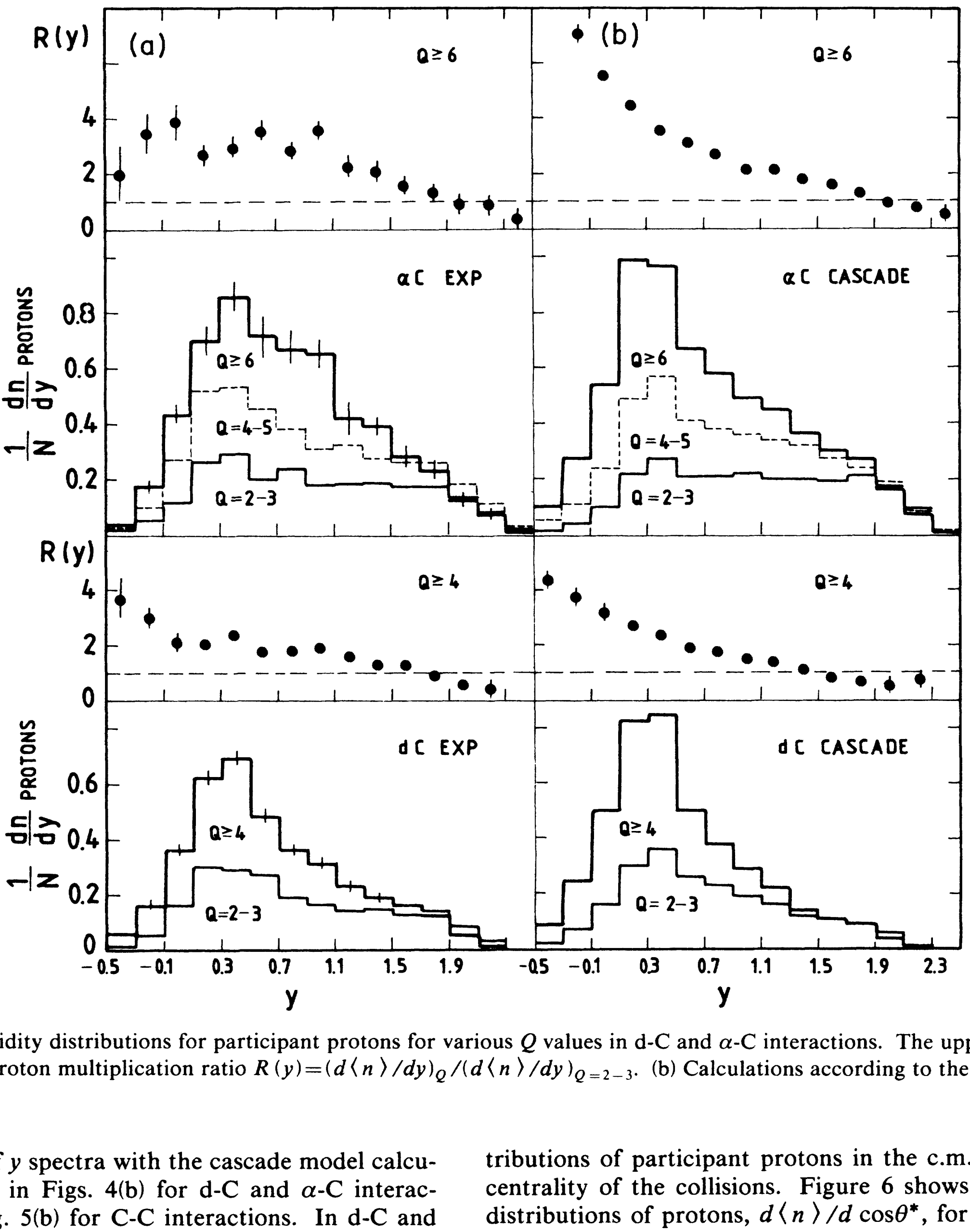

FIG. 4. (a) Rapidity distributions for participant protons for various $Q$ values in d-C and $\alpha$-C interactions. The upper part of the figure represents proton multiplication ratio $R(y)=(d\langle n\rangle/dy)_Q/(d\langle n\rangle/dy)_{Q=2\text{-}3}$. (b) Calculations according to the cascade model.

Comparison of $y$ spectra with the cascade model calculations is shown in Figs. 4(b) for d-C and $\alpha$-C interactions, and in Fig. 5(b) for C-C interactions. In d-C and $\alpha$-C interactions on $Q\leq 4$, the model satisfactorily reproduces the $y$ spectra of participant protons, whereas for higher $Q$, the model systematically overestimates proton multiplicity in the target fragmentation region. Consequently, in the cascade model the multiplication ratio $R(y)$ increases almost continuously with decreasing $y$. In C-C interactions even at $Q\geq 8$, the model overestimates both fragmentation processes. Therefore the model does not describe the form change of the rapidity distribution with increasing $Q$. The weakness of the model at high $Q$ is qualitatively illustrated in Fig. 5, where the multiplication ratio for $Q=4\text{-}5$ and $Q\geq 10$ is shown.

It appears that in collisions of two equal nuclei, the cascade model lacks a significant fraction of the stopping power provided by the nuclear medium. In collisions in which two equal nuclei are fully stopped, protons are emitted isotropically from the interaction point. For this reason, the correlation is studied between the angular distributions of participant protons in the c.m. system and centrality of the collisions. Figure 6 shows the angular distributions of protons, $d\langle n\rangle/d\cos\theta^*$, for $Q=2\text{-}3$ and $Q\geq 10$, in C-C interactions. These have clear peaks in the range $0.9<|\cos\theta^*|<1$, characteristic for angular distributions of protons in p-p interactions. However, some increases in proton multiplicity with $Q$ can be seen in the region of $0<|\cos\theta^*|<0.9$, in comparison with proton multiplicity within the peak region. The above confirms the ratio

$$R=\langle n_p(0.9<\cos\theta^*<1\rangle/\langle n_p(0<\cos\theta^*<0.1)\rangle$$

which has the value $R_{pp}=11.5\pm2.5$ for p-p interactions, the value $R_{Q=2\text{-}3}=16.2\pm3.3$ for $Q=2\text{-}3$ interactions, and $R_{Q\geq 10}=5.7\pm0.9$ for $Q\geq 10$ interactions. According to the cascade model these values are $R_{Q=2\text{-}3}=7.6\pm0.6$ and $R_{Q\geq 10}=9.2\pm0.7$.

Dependence of the $p_T$ distribution of participant protons upon $Q$ is shown in Fig. 7, in terms of the ratio

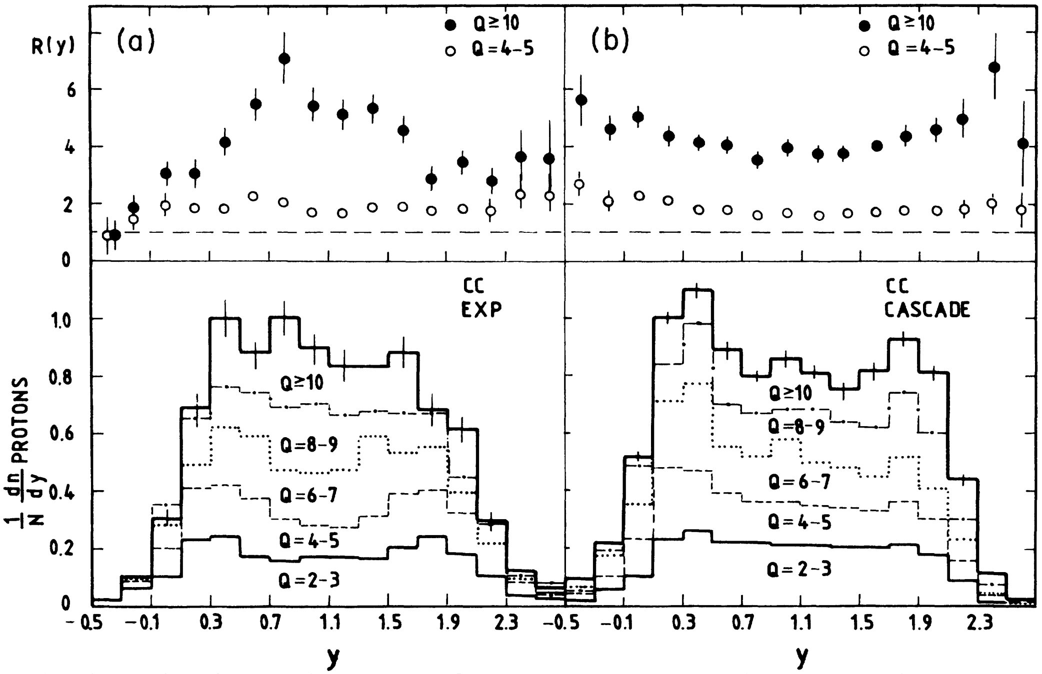

FIG. 5. (a) Rapidity distributions for participant protons for various $Q$ values in C-C interactions. The upper part of the figure represents proton multiplication ratio $R(y)$. (b) Calculations according to the cascade model.

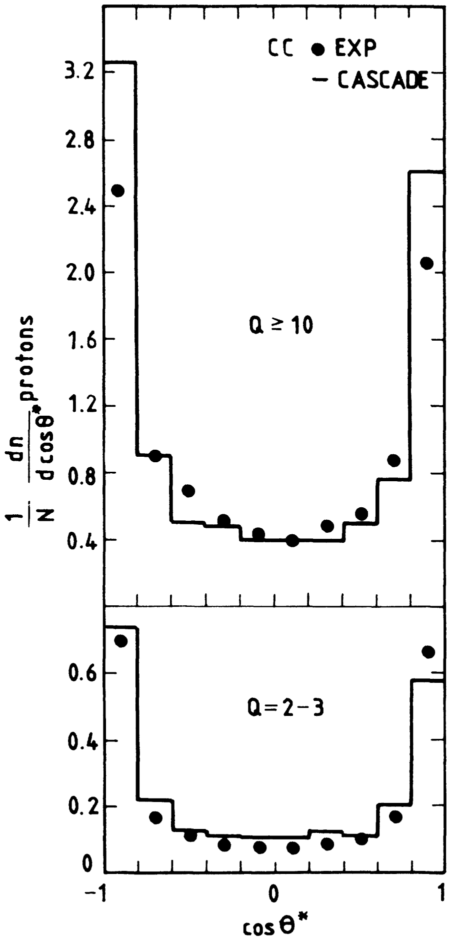

FIG. 6. Angular distributions of participant protons calculated in NN c.m. system for $Q=2-3$ and $Q\geq 10$ in C-C interactions.

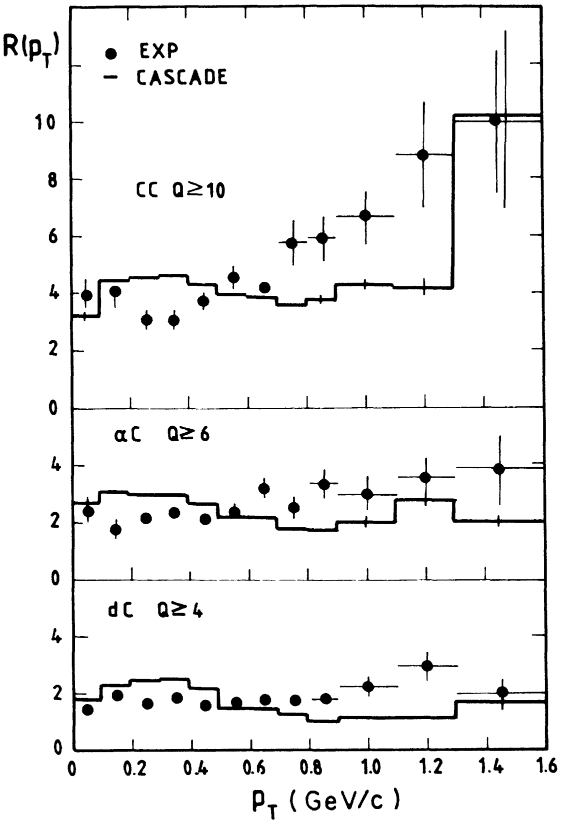

FIG. 7. Normalized ratio of the transverse momentum distributions $R_Q(p_T)=(d\langle n\rangle/dp_T)_{Q_{\max}}/(d\langle n\rangle/dp_T)_{Q=2-3}$ for d-C, $\alpha$-C, and C-C interactions.

$$R_Q(p_T)=(d\langle n\rangle/dp_T)_{Q_{\max}}/(d\langle n\rangle/dp_T)_{Q=2-3}\;.$$

This ratio normalizes the $p_T$ distributions for maximum $Q$ by the distributions for $Q=2$-3. It can be seen that with increasing $p_T$ the ratio $R_Q(p_T)$ also increases. This very weak effect in d-C interactions becomes stronger with increasing mass number of the projectile. The cascade model cannot describe the change of $R_Q(p_T)$ with $p_T$ and $Q$.

## CONCLUSION

The dependence of average values of kinematic variables and spectra of participant protons in (d,$\alpha$,C)C interactions at 4.2 GeV/$c$ per nucleon upon net charge $Q$ is investigated. In d-C and $\alpha$-C interactions the average momentum and rapidity of participant protons both decrease, while the emission angle increases with increasing $Q$. In collisions of nuclei of equal mass, $\langle p\rangle$, $\langle y\rangle$, and $\langle\theta_l\rangle$ are independent of $Q$. In all interactions analyzed, the average transverse momentum of participant protons increases with $Q$ from 3% to 15% with increasing mass of the projectile. Average transverse momentum of $\Lambda$ hyperons also increases with $Q$.[13] The mean kinematic variables of negative pions show a dependence on $Q$ which is similar to that of protons. The exception is $\langle p_T\rangle$, which, for pions, remains constant or decreases with $Q$.

In C-C interactions the $y$ spectra of participant protons changes shape with increasing $Q$. For lower $Q$ the contributions from the projectile and target are separable and the distributions have a two peak structure. For $Q\geq 8$, this bimodal shape disappears and most protons are produced from the central region.

The $p_T$ distributions of protons for various $Q$ show that the number of protons rises with higher transverse momenta. This rise becomes stronger with increasing mass number of the projectile.

The cascade model satisfactorily reproduces the dependence of $\langle p\rangle$, $\langle y\rangle$, and $\langle\theta_l\rangle$ on $Q$, as well as the $y$ spectra of protons for small values of $Q$. At higher $Q$ the model overestimates proton emission in the target fragmentation region for d-C and $\alpha$-C interactions. For C-C interactions the model overestimates proton emission in both fragmentations regions. Thus the model is incapable of describing the shape change of the $y$ spectra with $Q$. The model also cannot describe the dependence of $\langle p_T\rangle$ and the $p_T^-$ spectra upon $Q$.

The present data concerning the relation between participant proton characteristics and $Q$ reveal several features which are not explained within the Dubna version of the cascade model. The model does not demonstrate such difficulties with regard to meson production. Therefore protons appear to be more sensitive indicators of deviations from a simple independent nucleon approach.

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