Краткие сообщения ОИЯИ №3[60]-93 *JINR Rapid Communications No.3[60]-93*
УДК 539.172.8

EXPERIMENTAL STUDY OF MULTIPLICITY DEPENDENCE OF CUMULATIVE PION PRODUCTION IN FRAGMENTATION OF RELATIVISTIC DEUTERONS AND CARBON NUCLEI

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4.5·A GeV/c deuteron and carbon nucleus fragmentation into cumulative pions has been measured on various target nuclei in the range of the scale variable within 0.6—1.6 corresponding to the region around the kinematical limit of free nucleon-nucleon collisions. The target nucleus atomic weight dependence significantly differs from the volume type dependence on the atomic weight previously established for a fragmenting nucleus. A weak multiplicity dependence of the target nucleus fragmentation supports the limiting fragmentation picture of the process.

The investigation has been performed at the Laboratory of High Energies, JINR.

Экспериментальное исследование зависимости образования кумулятивных пионов от множественности при фрагментации релятивистских дейтронов и ядер углерода

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Исследована фрагментация дейтронов и ядер углерода с импульсом 4,5·A ГэВ/c в кумулятивные пионы на различных ядрах мишени в диапазоне масштабной переменной 0,6—1,6 вблизи кинематического предела свободных нуклон-нуклонных соударений. Зависимость от атомного веса ядра мишени значительно отличается от установленной ранее объемной зависимости от веса фрагментирующего ядра. Слабая зависимость от множественности фрагментации ядра мишени указывает на справедливость картины предельной фрагментации в этом процессе.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

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1. Introduction

One of the firmly established properties of the spectra of secondary particles produced in a fragmentation of nuclei is a transition to an asymptotic behaviour [1,2] starting from a primary collision energy of 4·A GeV when a rapidity gap $\Delta y \approx 2$ between colliding nuclei is reached. The invariant differential cross-sections presented vs relativistic invariant scale variables are becoming weakly dependent on the collision energy and the type of colliding hadrons and nuclei [4,5,6,7].

The transition to the regime of limiting fragmentation of nuclei in a few GeV collision energy region is closely related to the transition to particle production with momenta kinematically forbidden for free nucleon-nucleon collisions. It makes possible to provide at least the same rapidity gap between a fragmenting nucleus and a secondary particle. The relativistic invariant approach [9] to the multiple process analysis in a 4-velocity space gives a unification of these conditions on the basis of the depletion correlation principle.

The measurements of cumulative hadron spectra, i.e. hadrons produced beyond a kinematic limit of a free nucleon-nucleon collision in a limiting fragmentation region of nuclei, were carried out over a wide variety of colliding hadrons and nuclei with a detailed analysis of production angle and momentum dependences. The behaviour of the differential cross-sections was followed over nine orders of magnitude and the few nucleon kinematic limits of a collision were reached. However, an inclusive approach has the definite limits for answering the questions about a cumulative hadron production mechanism.

A limiting fragmentation picture [3] should be systematically verified in nucleus-nucleus collisions with measurement of a secondary particle multiplicity. A simultaneous multiplicity study opens up an opportunity to compare inclusive spectra of secondary particles at various degrees of reaction inelasticity, and to turn the process interpretation in terms of a number of wounded nucleons, a collision impact parameter and other theoretical model related parameters. In particular, the semiexclusive approach gives an additional chance to test the ideas about a quark origin [8] of a cumulative π-meson production through an experimental estimate of the pion formation length and nuclear transparency.

2. Scale Variable — Cumulative Number

Let us define a kinematic region for cumulative particle production. The minimum fractions of the 4-momenta of colliding nuclei, X_I and X_{II}, satisfying the total 4-momentum conservation law for production of a particle with the 4-momentum P_1 and the mass m_1 are expressed by the relativistic invariant equation for a squared minimum 4-momentum of a reaction recoil [8] — cumulative number:

$$(X_I P_I + X_{II} P_{II} - P_1)^2 = (X_I m_0 + X_{II} m_0 + m_2)^2,$$

where P_I and P_{II} are the 4-momenta of colliding nuclei per nucleon; m_0, nucleon mass; m_2, the mass for additional particles needed to obey the quantum number conservation rules (for pions $m_2 = 0$). Putting $X_{II} = 1$ for the target nucleus, one can derive an expression for X_I (the cumulative number of a projectile nucleus) with the mass corrections taken into account:

$$X_I = \frac{(P_{II} P_1) + m_0 m_2 + (m_2^2 - m_1^2)/2}{(P_I P_{II}) - m_0^2 - (P_I P_1) - m_0 m_2}.$$

The physical meaning of the variable X_I is becoming more clear in a high energy approximation $X_I \approx P_{1z}/P_{beam}$, where P_{1z} and P_{beam} are a particle longitudinal momentum and a nucleon mean momentum in a projectile nucleus. The variable X_{II} has a well-known light cone variable as a high energy limit. In a limiting fragmentation region of a nucleus I the particle spectra have an exponential dependence of X_I and practically don't depend on X_{II} [13].

In the previous paper [10] we measured the target dependence of the spectra of cumulative pions in a fragmentation of relativistic deuterons. The present study includes pilot results on the associated charget multiplicity of the process of a deuteron and a carbon nucleus fragmentation on carbon and lead targets.

3. Experimental Procedure

The measurements were taken on a 4.5·A GeV/c deuteron and carbon nucleus beam of Dubna Syncrophasotron with an intensity of $10^5 - 10^6$ s^{-1}. The SPHERE forward magnetic spectrometer [10] (fig.1) consisted of:

- a beam particle monitoring telescope consisting of three scintillation counters; the amplitude spectrum of one of the counters is shown in fig.2;

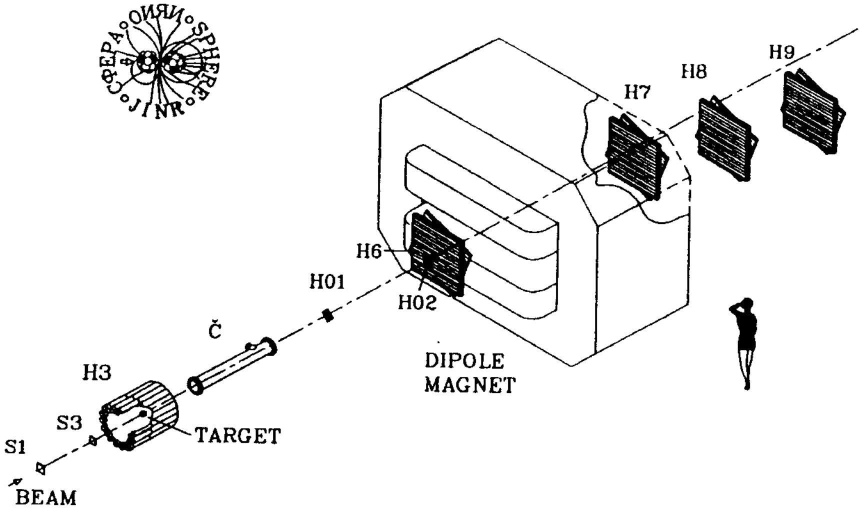

Figure 1. Layout of the SPHERE forward scintillation spectrometer

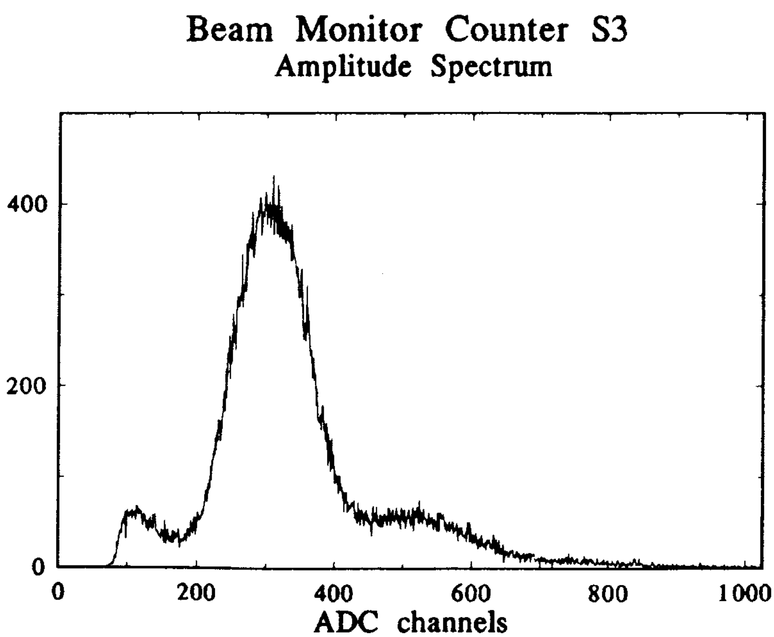

Figure 2. The amplitude spectrum of a beam monitoring counter

- a changeable target placed at 700 cm in front of the magnet center; the carbon and lead target thicknesses are 3.24 g/cm^2 and 10.5 g/cm^2; the liquid hydrogen target was used to obtain a reference fragmentation spectrum; the hydrogen container has a spherical shape with a 60 mm internal diameter;

- a two-layer cylindrical scintillation hodoscope intended for a total and hard charged multiplicity tagging in an azimuthal angle from 20° to 90°; each cylinder consists of 18 counters providing a polar angle segmentation; the hodoscopes are interleaved by a 40 mm thick steel absorber suppressing a soft muplitplicity up to a proton transverse momenta $p_T < 600$ MeV/c;
- a dipole frame type magnet with a 68 cm gap; the poles are 100 cm wide and 150 cm long; the maximum field in the magnet center is 0.82 T;
- a high-pressure gas threshold Cherenkov counter; it provides a 1 ns timing resolution;
- two 16×16 cm^2 hodoscopes; each hodoscope consists of two planes containing 16 counters $160\times9\times3$ mm^3 in size;
- four three-coordinate hodoscopes of a 1 m^2 area; each hodoscope plane contains twenty three $1000\times40\times5$ mm^3 counters.

The solid angle acceptance of the spectrometer is about 10^{-4} sr and the momentum acceptance extends from 2.5 to 6 GeV/c covering X_I from 0.5 to 2.0 in a single exposition. The main points of the event selection procedure are following;

- an effective selection of relativistic π-mesons are worked out by the trigger logic; a trigger is provided by a coincidence of signals from the beam monitor, the Cherenkov counter, and the hodoscopes placed behind the magnet; the timing spectra of coincidences are shown in fig.3;
- a pion track was selected in the negative charge wing of the magnet; the momentum is calculated from the angle between the horizontal projection of a deflected track and the primary beam axis; the dispersion of production angles is negligible;
- a hitted counter number of the inner layer of the cylinder hodoscope is assigned the total charged multiplicity of an event, n_{ch}; a lower multiplicity cut $n_{ch} > 0$ in the data analysis reflects a trigger logic selection applied for a reduction of a target-off contribution;
- a hard charged track multiplicity, N_{ch} is estimated by the number of azimuthal angle coincidences of hitted counters of the inner and outer layers.

Trigger Timing
Monitor - Detector Coincidence TDC Spectra

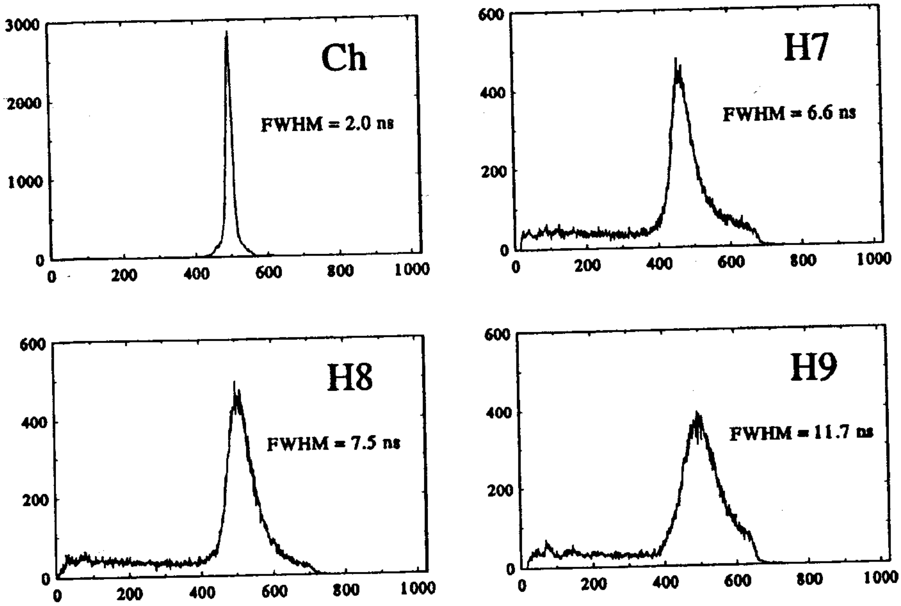

Figure 3. Timing spectrum of *Ch*, *H7*, *H8*, *H9* trigger coincidences

4. Deuteron Fragmentation

The dependence of the projectile nucleus fragmentation cross-section on the target nucleus mass number, the A dependence, is a simplest way to draw preliminary conclusions about the interaction between a π meson and a target nucleus. It is convenient to describe A dependence by a power law parameterization, A^{α}.

We have measured [10] the power value of the A dependence of the cross-section for $4.5 \cdot A$ GeV/c deuteron fragmentation into cumulative pions on carbon, aluminimum, copper and lead nuclei for X_I within 0.8—1.2 and the mean value $\langle \alpha \rangle = 0.27 \pm 0.09$ was obtained in this interval. The target atomic mass number dependence significantly differs from the volume type dependence [4] on the fragmenting nucleus atomic mass number where a value of α around 1 was found. The obtained value seems to indicate a peripheral character of the interaction between a target nucleus and a deuteron fragmenting into a cumulative pion. Formerly similar conclusions were drawn by the Berkeley group [12] for fragmentation of light relativistic nuclei into pions — a power value of 0.4 was obtained for α particles. In a more general sense, such asymmetry in A dependences follows a limiting fragmentation concept.

We have estimated mean values and r. m. s. of multiplicity distributions; $\langle n_{ch} \rangle = 1.32$ with $\sigma_{n_{ch}} = 1.34$ for d-C collisions; for d-Pb — 2.46 and 2.24, respectively. The fraction of events containing a hard track candidate doesn't exceed 15% for carbon target and 16% for lead one. Thus, the mean values and a hard component fraction show a weak dependence on the fragmenting nucleus atomic mass number and point in favour of the peripherial collision picture.

5. Carbon Fragmentation

As a continuation of the deuteron fragmentation study we have carried out similar measurements of 4.5 · A carbon nucleus fragmentation. The pion spectra are obtained on carbon and lead targets. Besides, the liquid hydrogen target was used to get reference data for nuclear media effects. Typical spectra of pions produced in carbon-carbon collisions at various reaction multiplicitis are shown in fig.4.

Our main interest is to derive physical conclusions on the basis of spectrum ratio behaviour. These ratios are acceptance and systematic correction free values. The mean values $\langle R \rangle$ and r. m. s. σ_R of each set of the ratio values corresponding to the definite multiplicity cut were calculated and a ratio

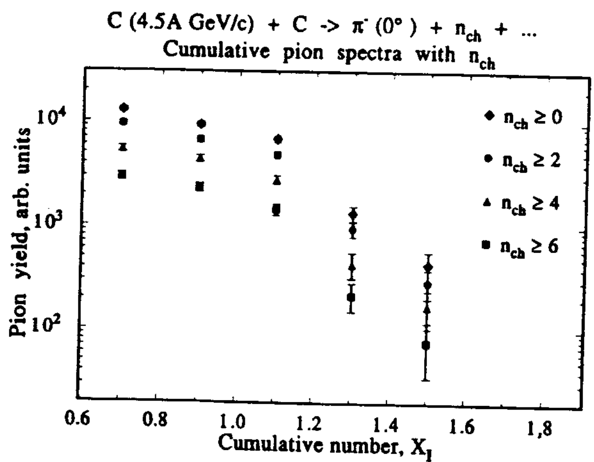

Figure 4. Spectra of straightforward produced pions in carbon-carbon collisions vs scale variable X_I at various cuts on a total event multiplicity, n_{ch}

$\sigma_R/\langle R\rangle$ was accepted as a relative estimate of a spectrum distortion in the covered region of X_I, $0.6 < X_I < 1.6$.

5.1. Carbon — Carbon Collisions. The experimental points in fig.4 correspond to the bin centers of the variables X_I. The characteristic feature of the spectra is similarity of the shape at different multiplicities of the reaction, n_{ch} and this leads to a stability of the ratios of the spectra to the inclusive one (fig.5) within 10% margins around a mean value of each set of points. Fig.6 shows the ratios of the spectra to the inclusive pion spectrum obtained on the liquid hydrogen target. In this case a spectrum distortion can be estimated at a level of less than 50%.

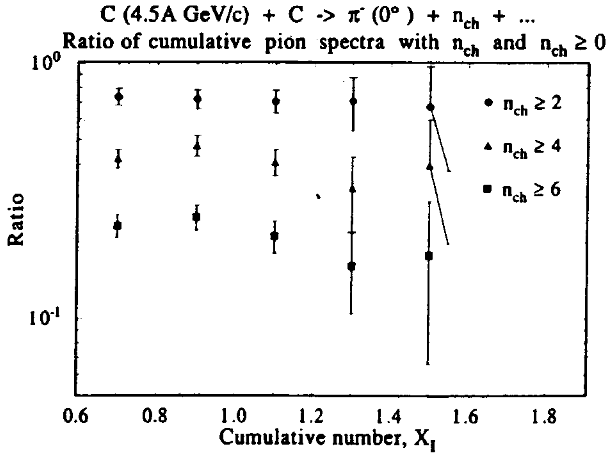

Figure 5. Ratio of the pion spectra produced on a carbon target with variation of n_{ch} to the inclusive spectrum

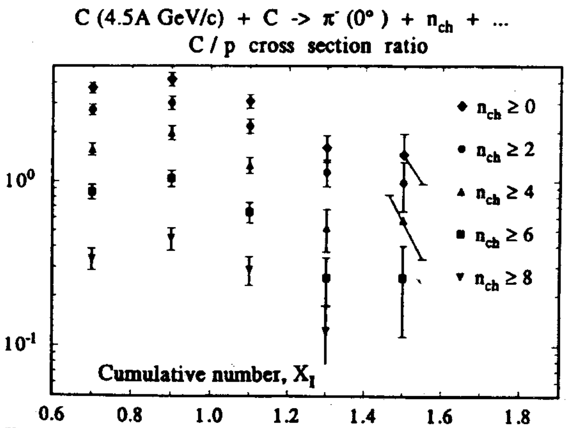

Figure 6. Ratio of the pion spectra produced on a carbon target to the inclusive spectrum from the hydrogen target

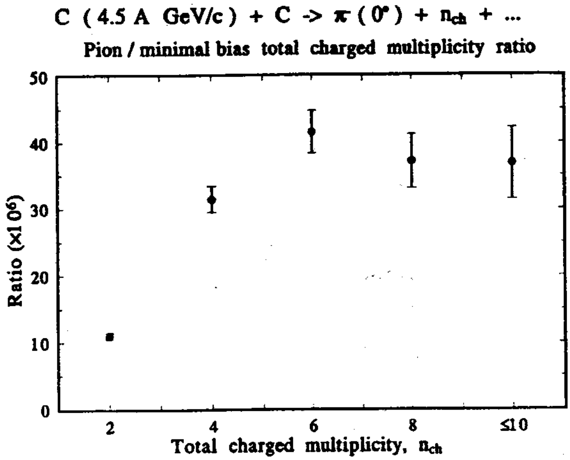

Figure 7. Ratio of n_{ch} multiplicity distribution with a pion produced in a cumulative number range $0.6 < X_I < 1.6$ to a minimal bias event multiplicity. The multiplication factor on the ordinate axis takes into account the difference in beam particle fluxes

As it was established in the inclusive experiments [8] the invariant differential cross-sections of cumulative particle production fall down to three orders of magnitude with an increase of the scale variable from 0.6 to 1.6. Thus, the estimated distortion appears to be insignificant with respect to the cross-section variation.

We compared the multiplicity distribution corresponding to cumulative pion production and the minimal biased multiplicity distribution of carbon-carbon collisions in an angular range of the cylinder hodoscope. The ratio of the distributions is shown in fig.7. A rapid raise and a subsequent saturation can be seen with a growth of a total event multiplicity to a total charge limit.

5.2 Carbon-Lead Collisions. An upper total charged multiplicity cut was applied $n_{ch} < 8$ for a lead target in order to suppress a contribution of multiple interactions of beam nuclei and nuclear fragments. This limit is derived from the experimental data putting a demand on the linear behaviour of an accompanying multiplicity yield with a target thickness. In the case of carbon-lead collisions we are able to estimate the event inelasticity by an accompanying hard track multiplicity, N_{ch} (see fig.8).

Figure 9 gives limit of a distortion with respect to the inclusive spectrum within a margin of 30%. For a fragmentation on target protons (fig.10) we obtain distortion upper estimate of 60%. For the hard multiplicity part (fig.11) a rapid fall down can be seen with respect to a hard multiplicity part of minimal bias events.

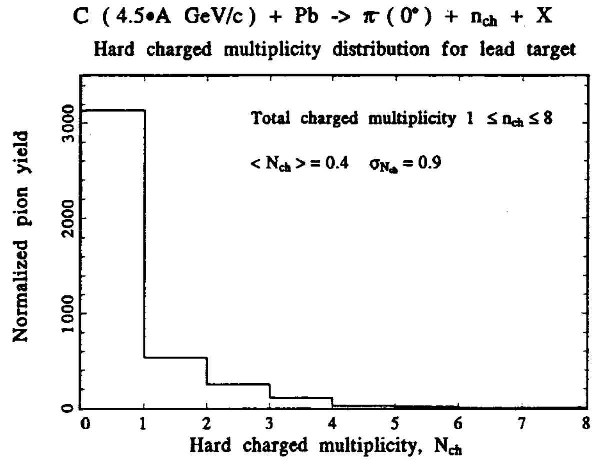

Figure 8. The multiplicity distribution of hard tracks ($P_T > 600$ MeV/c for protons) N_{ch} in the cylinder hodoscope

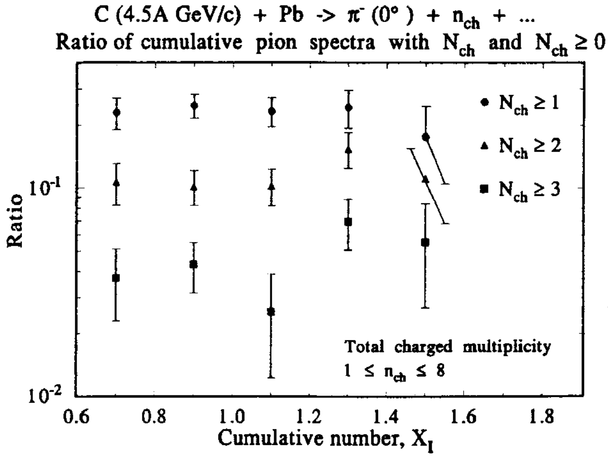

Figure 9. Ratio of the pion spectra produced on a lead target with variation of hard multiplicity N_{ch} to the inclusive spectrum

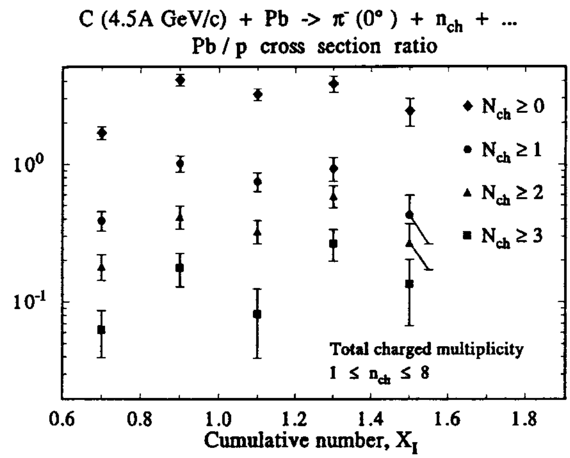

Figure 10. Ratio of the pion spectra produced on a lead target to the inclusive spectrum from the hydrogen target

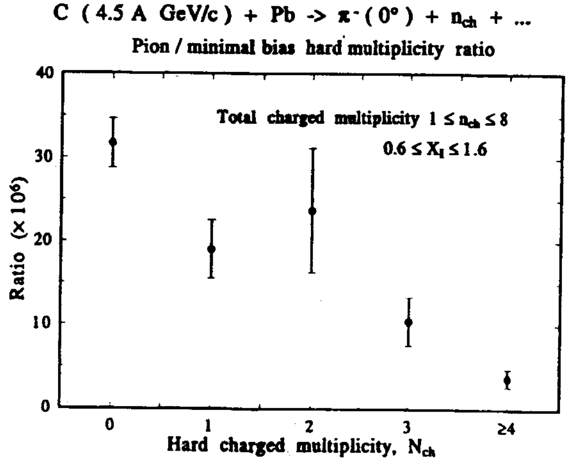

Figure 11. Ratio of N_{ch} multiplicity distribution with a pion produced in a cumulative number range $0.6 < X_I < 1.6$ to a minimal bias event multiplicity

6. Conclusions

To summarize, the influence of a target nucleus on cumulative π^- meson spectra straightforward produced in a fragmentation of light relativistic nuclei was studied at various degrees of the reaction inelasticity.

We doesn't observe an indication of effects of a significant modification of the spectrum shape with respect to the inclusive spectra obtained on proton, carbon and lead targets. It points to a weakness of secondary interaction contribution in a cumulative pion production. We consider these results as a confirmation of the validity of the limiting fragmentation hypothesis applied to high multiplicity nucleus-nucleus collisions.

A natural extension of this study is a systematic shift to more inelastic collisions. Spectra of cumulative pions are considered to be a manifestation of the quark-parton structure function of nucleus [8]. From this point of view our approach permits «tagging» of «superfast» quarks in a fragmenting nucleus and opens up possibility to study details of hadronization process in correlation measurements.

Besides, it appears to be particularly interesting to study nuclear collisions in a region where both X_I and X_{II} are essential [13]. For instance, highly inelastic collision could lead to a dramatic change of a power of the A dependence. In this case a cumulative particle tags a process of collision of high momentum components in both nuclei or fluctuations of nuclear density.

Acknowledgements

This study was carried out in the framework of the SPHERE Project of the Joint Institute for Nuclear Research. We express our sincere gratitude to Academician A.M.Baldin for stimulating discussions and critics. We are also indebted to the members of the Dubna Synchrophasotron Staff and the Beam Transport Group. An important financial support was provided from the Russian Fund of Fundamental Researches (grant №93-02-3773).

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Received on June 22, 1993.