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# DETAILED STUDY OF NUCLEAR DENSITY AND CHARGE DISTRIBUTION EFFECTS IN CUMULATIVE PARTICLE PRODUCTION

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Detailed studies of A-dependence of a cumulative particle production carried out on beams of protons and light nuclei have shown similarities in a behaviour of the cross sections per nucleon on different beams in a wide range of fragmenting nuclei. The cross sections of a cumulative particle production are closely correlated with a nuclear density in a region of light nuclei. There is a correlation of cross sections with a charge density distribution in a region of medium weight nuclei. The cross sections of positive and negative particles are correlated with a relative content of protons and neutrons in nuclei. A large neutron excess in heavy nuclei doesn't produce a difference of the cross sections for positive and negative pions (both are approximately equal).

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

## Детальное изучение влияния ядерной плотности и распределения заряда на кумулятивное рождение частиц

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Детальное изучение A-зависимости рождения кумулятивных частиц на пучках протонов и легких ядер показывает сходное поведение сечения на нуклон для разных пучков в широкой области фрагментирующих ядер. Сечение рождения кумулятивных частиц коррелирует с распределением ядерной плотности для легких ядер. Корреляция с плотностью заряда наблюдается в области ядер со средним весом. Сечение рождения положительных и отрицательных частиц коррелирует с относительным содержанием протонов и нейтронов в ядрах. Большой нейтронный избыток для тяжелых ядер не сказывается на сечении рождения положительных и отрицательных пионов (оба сечения примерно равны).

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

An investigation of a cumulative particle production made it possible to establish general features of a target nucleus fragmentation in hadron-

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nucleus and nucleus-nucleus collisions [1,2]. The most important one is a universality of an exponential slope parameter of scale variable spectra of cumulative particles in a wide range of collision energy and fragmenting nuclei. On the basis of these results a quark-parton structure function of nucleus was introduced [3], which was supposed to reflect a momentum quark distribution in nuclei. A behaviour of the structure function was studied in a range of a relativistic invariant scale variable $0.35 < X < 3.5$ [4]. A relativistic invariant definition of $X$ can be found in [4].

Our previous results on A-dependence with proton beams [1,2,3] were confirmed in the paper [5].

A dominant feature in a behaviour of an $A$-dependence of cross sections of cumulative particles ($\pi$, $K$, $p$, bound systems like deuterons, tritons) is a rapid growth of cross sections in the region of the lightest nuclei which becomes more flat with a growth of a mass number of fragmenting nuclei. For pions this change in a growth corresponds to $A \approx 30$; and for protons and baryon fragments, to $A \approx 100$.

A fragmentation of the following nuclei was studied in [1,2,3,4,5]: D, $^4$He, $^6$Li, $^7$Li, Be, C, Al, Si, $^{54}$Fe, $^{56}$Fe, $^{58}$Fe, $^{58}$Ni, $^{61}$Ni, $^{64}$Ni, $^{64}$Zn, $^{114}$Sn, $^{124}$Sn, Pb. Separated isotope targets give an opportunity to study a cumulative production at a fixed charge of nuclei with a variation of a neutron content. On the other side, it makes possible to vary a charge of nucleus at a fixed mass number.

The dependence of a ratio of structure functions on a density of nuclei ($^6$Li, $^{12}$C, $^{40}$Ca) at $X$ less than 0.06 was precisely measured by the NMC collaboration [6]. Our data were taken in a range of the scale variable $0.7 \leq X \leq 1.4$. To analyze density effects we used the same expression for a density of nuclei as in the paper [6] of the NMC collaboration:

$$\rho(A) = A \,/\, [\tfrac{4}{3}\pi\, (\tfrac{5}{3} < r^2 >)^{3/2}],$$

where $< r^2 >$ is the mean square nuclear charge radius [7].

Inclusive invariant cross sections of secondary particles ($\pi^+$, $\pi^-$, $p$, $d$) normalized per nucleon of a fragmenting nucleus were measured at a production angle of 120° with a momentum of 0.5 GeV/c for collisions of 4.5$A$ GeV/c deuterons with nuclei [5]. An expression for a cross section is shown below.

$$\frac{1}{A} \cdot E\frac{d\sigma}{dp} \equiv \frac{1}{A} \cdot \frac{E}{p^2}\frac{d^2\sigma}{dp d\Omega} \, (\mathrm{mb \cdot GeV^{-2} \cdot c^3 \cdot sr^{-1} \cdot nucleon^{-1}}).$$

Figure 1 shows $A$-dependence of the cross section per nucleon in a region of the lightest nuclei. There is a definite correlation of the cross

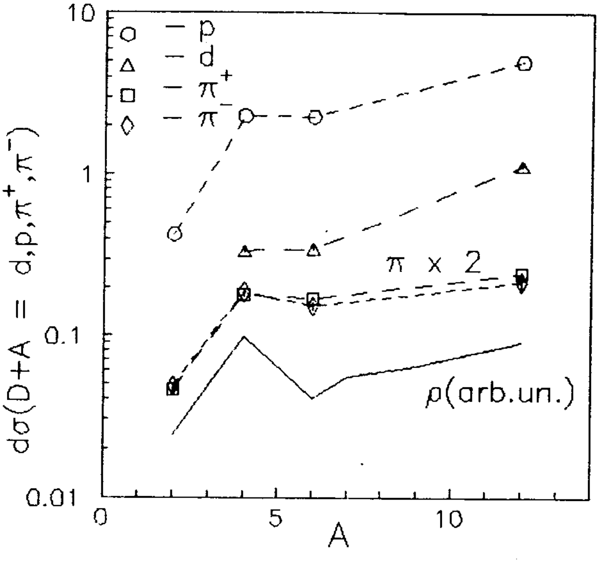

**Fig.1.** $A$-dependence of cross sections of a cumulative particle production in $D + A \to c + \ldots$ ($\theta = 120°$)

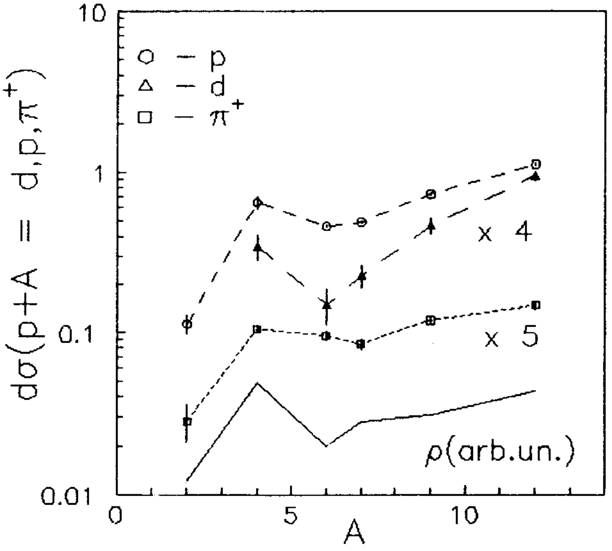

**Fig.2.** $A$-dependence of cross sections of a cumulative particle production in $p + A \to c + \ldots$ ($\theta = 180°$)

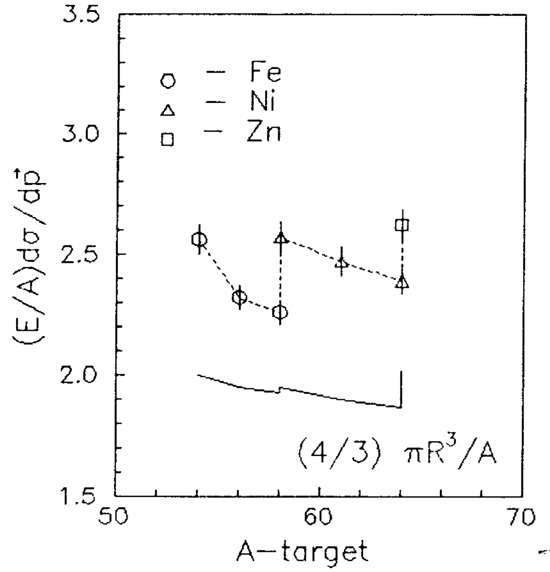

Fig.3. $A$-dependence of cross sections of cumulative particle production in $p + A \to p + \ldots$ ($p_0$ = = 8.9 GeV/c, $\theta$ = 180°)

sections with a density of a fragmenting nucleus (lower curve). A ratio of helium to deuteron nuclear densities is equal to 4.2 and corresponds to a growth of a relative yield for protons by a factor of 5.38±0.22; for $\pi^+$, 3.90± ±0.13; for $\pi^-$, 3.86±0.13. A density of $^6$Li is 2,5 times lower than $^4$He, but cross sections per nucleon are approximately equal. A density of a carbon nucleus is 2.25 times higher than for $^6$Li and corresponds to the ratio of cross sections 2.22±0.06 for protons, 3.26±0.09 for deuterons, 1.43±0.04 for $\pi^+$and 1.42±0.17 for $\pi^-$.

Figure 2 shows a similar data for collisions of 8.9 GeV/c protons with nuclei [4,8]. Secondary particles were observed at an angle of 180° with momenta of 0.5 GeV/c. A correlation between a density (lower curve) and a cross section is more clear, especially for a transition from a helium nucleus to a lithium one.

As a mass number $A$ increases, a density tends to a constant value, and an observation of such a correlation becomes less probable. Nevertheless, irregularities related with a fraction of a neutron and proton content were seen in this region [2].

It was experimentally shown that proton production cross sections are independent of a neutron excess at a fixed charge of a nucleus. This effect was called an isotopic effect. In paper [9], this conclusion was confirmed and an isotonic effect was established, i.e., an independence of a neutron yield on a number of protons in a nucleus. A detailed study of a cumulative particle production [5] on nuclei with a well defined number of protons and neutrons made it possible to obtain a qualitatively new information on these phenomena.

Proton production cross sections on isotopes of Fe, Ni, and Zn [8] are shown in fig.3. A primary beam is 8.9 GeV/c protons, a secondary proton

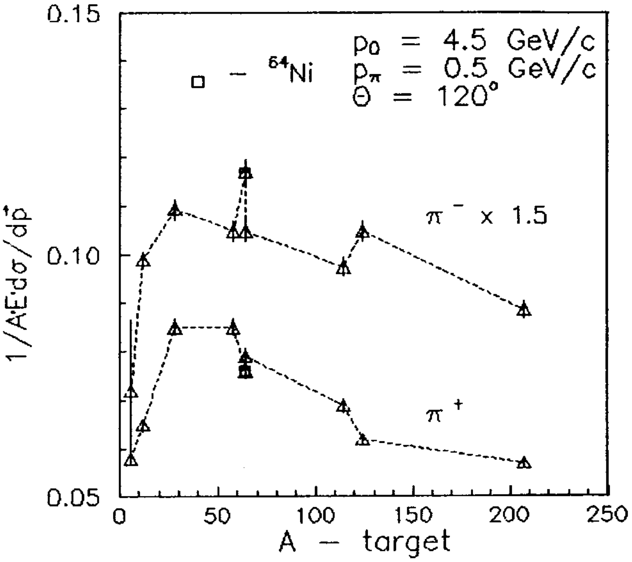

Fig.4. A-dependence of cross sections of cumulative particle production in $p + A \rightarrow p + \ldots$

momentum is 0.5 GeV/c; a production angle, 180°. The experimental points are connected with a dashed line, and the lower curve fits the formula

$$V = \frac{4}{3}\pi R^3 \;/\; A,$$

which we assign as a charge density of a nucleus. $R = \langle r^2 \rangle^{1/2}$ is a mean radius of a nucleus. There is a correlation between the cross sections and this parameter, especially for Ni and Zn isotopes. The cross section shows a sharp growth at a small growth of a charge from $^{58}$Fe to $^{58}$Ni, from $^{64}$Ni to

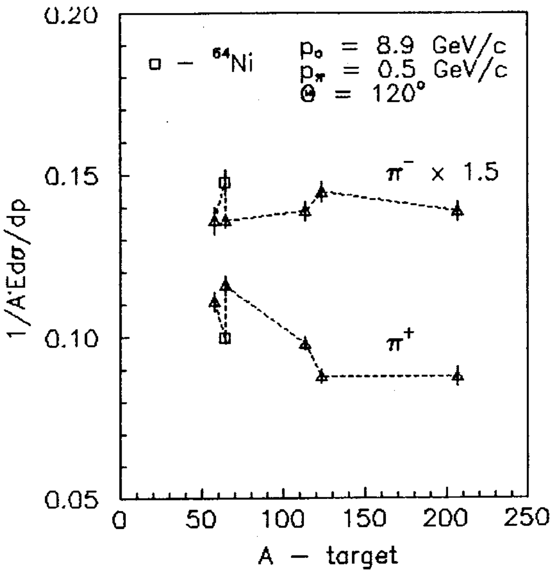

Fig.5. A-dependence of cross sections of a cumulative particle production in $p + A \rightarrow p + \ldots$

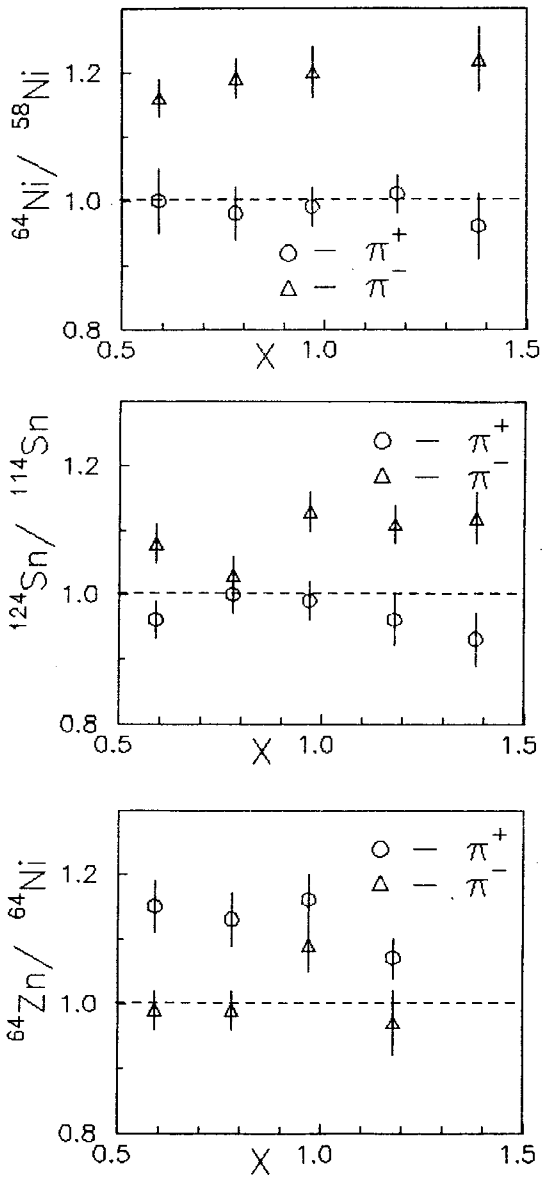

Fig.6. Ratio of cross sections for positive and negative pions

$^{64}$Zn (Z = 26, 28, 30). The results on $\pi^+$ and $\pi^-$ production in collisions of 4.5 and 8.9 GeV/c protons with nuclei are shown in figs.4 and 5. Pions were observed with 0.5 GeV/c momentum at an angle of 120°. The isotopic effect can be seen on both figures.

We studied the isotopic effect for pions and protons in a range of secondary particles momenta from 0.3 up to 0.7 GeV/c. Figure 6 (pions) and fig.7 (protons) show ratio of cross sections vs scale variable $X$, corresponding to momenta of this range. It is supposed a ratio of cross sections is proportional to a ratio of quark-parton structure functions of nuclei. Let us describe it in detail.

Cross sections in a $^{64}$Ni/$^{58}$Ni combination (same $Z$, different $N$) are equal for positive pions and follow to a neutron excess for negative ones. For a $^{64}$Zn/$^{64}$Ni combination we observe an opposite situation. A behaviour of a $^{124}$Sn/$^{114}$Sn combination is similar to the first one.

For protons (fig.7) a $^{64}$Ni/$^{58}$Ni combination shows an equality of cross sections or an independence of cross sections on a neutron excess. In case of a $^{64}$Zn/$^{64}$Ni combination a dominating role of a charge of a nucleus is seen

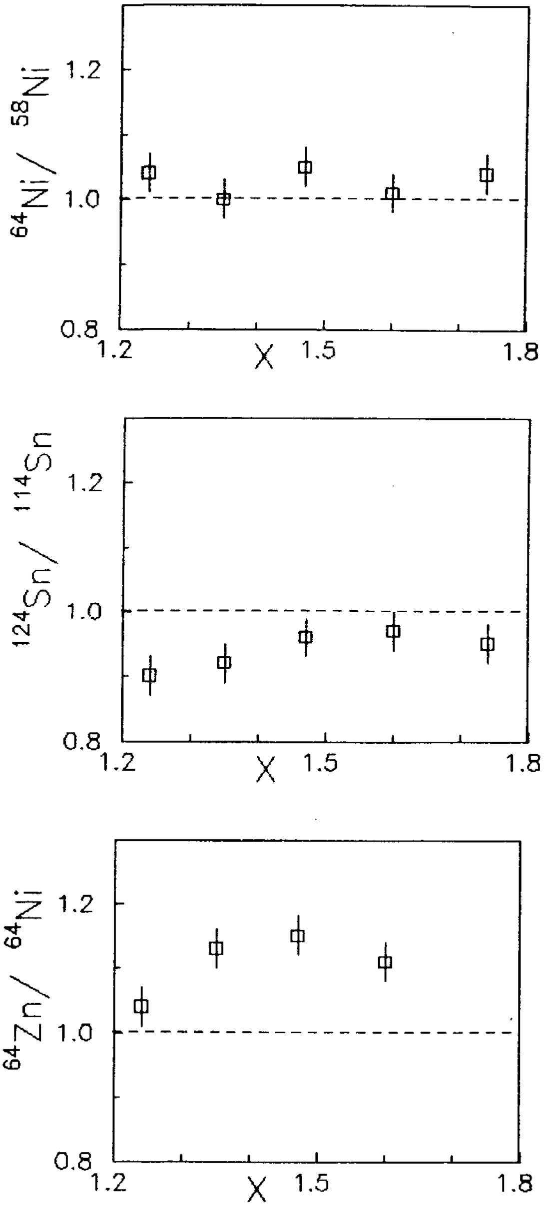

**Fig.7. Ratio of cross sections for protons**

for protron production. A $^{124}$Sn/$^{114}$Sn ratio is different from a constant and less than unity.

Let us make a summary of our conclusions:

- the cross sections of cumulative particle production are closely correlated with a nuclear density in a region of light nuclei;
- there is a correlation of cross sections with a charge density distribution in a region of medium weight nuclei;
- the cross sections of positive and negative particles are correlated with a relative content of protons and neutrons in nuclei;
- a large neutron excess in heavy nuclei doesn't produce a difference of the cross sections for positive and negative pions (both are approximately equal);
- these conclusions are considered as additional test of models of the cumulative effect and, in general, models describing collisions of relartivistic nuclei.

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