

## $\pi^0$ production in $dC$ - and $dCu$ -interactions at a momentum of 4.5 GeV/c per nucleon

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**Abstract.** We report on measurements of neutral pion production in the inclusive reactions  $d + C \rightarrow \pi^0 + x$  and  $d + Cu \rightarrow \pi^0 + x$  at an incident momentum of 4.5 GeV/c per nucleon. The experiments were performed on the LHE 90-channel lead glass  $\gamma$ -spectrometer. The cross sections were measured over the kinematical region specified by the inequalities  $\theta_\pi \leq 16^\circ$  and  $E_\pi \geq 2$  GeV (in the laboratory frame). The cumulative number and transverse momentum dependencies of the exponent  $n$  in the invariant cross section parameterization  $Ed^3\sigma/d^3p \sim A_t^n$  are investigated by comparing of the observed cross sections for  $\pi^0$  production on carbon and copper targets in the intervals  $0.6 \leq X \leq 1.8$  and  $0.04 \leq P_T^2 \leq 0.40$  (GeV/c)<sup>2</sup>. The double differential cross section for the reaction  $d + C \rightarrow \pi^0 + x$  is measured using statistics of about  $4.5 \cdot 10^4 \pi^0$  mesons. On the basis of these data we verified the so-called cluster mechanism of  $\pi^0$  production. We have compared our data for the reaction  $d + C \rightarrow \pi^0 + x$ , extrapolated to  $\theta_\pi = 0^\circ$ , with the data from another experiments on  $\pi^-$  production:  $d + C \rightarrow \pi^-(0^\circ) + x$  ( $P = 1.75$  and  $2.88$  GeV/c per nucleon) [1];  $p + d \rightarrow \pi^-(180^\circ) + x$  and  $p + d \rightarrow \pi^+(180^\circ) + x$  ( $P = 8.9$  GeV/c per nucleon) [2];  $d + p \rightarrow \pi^-(0^\circ) + x$  ( $P = 8.9$  GeV/c per nucleon) [3]. The invariant cross sections were approximated by an exponential function  $Ed^3\sigma/d^3p \sim \exp(-X/X_0)$ . The slope parameter  $X_0$  at different kinetic energies of the projectiles in the range of  $1.05 \div 8.0$  GeV per nucleon is determined.

## 1 Introduction

We report here on measurements of inclusive  $\pi^0$  production by relativistic deuterons on carbon and copper targets. The fragmentation of nuclei in high energy collisions into elementary particles with momenta far exceeding the average momentum per nucleon in the nucleus is one of the most interesting phenomena in high energy physics. This phenomenon, so-called cumulative production of particles was first observed by A.M. Baldin [4]. As in the previous investigations of our group [5–7], we aim at clarifying the mechanism of neutral pion emission near and beyond the kinematic limit for free nucleon-nucleon and nucleon-nucleus collisions. We have also investigated how  $\pi^0$  production depends on the number of nucleons in the target and compared our results with quark-parton models of the nucleus [8].

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Our experiments allow to study the double differential cross section of the reaction  $d + C \rightarrow \pi^0 + x$  and thus to study the properties of objects (hadronic clusters of fireballs, quarks, six-quark configurations) responsible for pion production in the above-mentioned kinematical region and to estimate the transverse component of valence quark momenta in protons and nuclei. Moreover, on the basis of this cross section we have been able to extrapolate our data to  $\theta_\pi = 0^\circ$ , which allows us to compare them correctly with the data from another experiments on  $\pi^-$  production.

## 2 Experiment

The experiment was performed at the Synchrotron of the High Energy Laboratory using a 90-channel lead glass  $\gamma$ -spectrometer. Our experimental setup, described in detail in the [5, 9], allows to measure both the energies and emission angles of photons from  $\pi^0$  decays. To monitor the number of beam particles hitting the target, a monitor telescope composed of three scintillation counters was used. For charge particle identifications 40 scintillator counter hodoscopes were used in front of the  $\gamma$ -spectrometer resulting in a 99% detection probability for charged particles.

Carbon and copper targets were exposed to a beam of deuterons with a momentum of 4.5 GeV/c, a momentum spread of  $\Delta p/p = \pm 2\%$  and an intensity up to  $10^5$  particle per pulse. The distance along the beam between the target center and the upstream face of the spectrometer was 340 cm for the carbon target and 520 cm for the copper target. The corresponding acceptances in the laboratory emission angle for  $\pi^0$  mesons were  $\theta_\pi \leq 16^\circ$  and  $10^\circ$ , respectively. About  $2 \cdot 10^5$  triggers for the carbon target and  $1.6 \cdot 10^5$  triggers for the copper target have been recorded during this experiment.

## 3 Event selection

The  $\pi^0$  mesons are detected through their two-photon decay mode as a narrow peak in the invariant mass distribution. Photons are recognized as isolated and confined clusters (an area of adjacent modules in the  $\gamma$ -spectrometer with a signal exceeding the detection threshold). The photon energy is calculated from the energy of the cluster by applying a position-dependent leakage correction. Assuming that the photon originates at the target, its direction is determined from the geometrical position of the constituent crystals, weighted by the corresponding energy deposits.

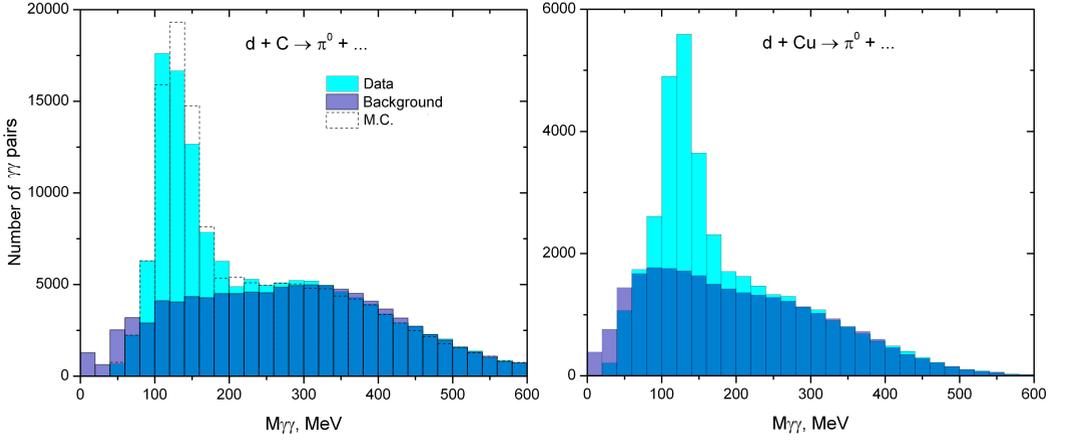
Inclusive spectra of  $\pi^0$  have been extracted from the raw data under the following selection criteria:

- (1)  $N_\gamma \geq 2$ ;
- (2)  $E_\gamma \geq 500$  MeV;
- (3)  $E_{\gamma\perp} \geq 120$  MeV;

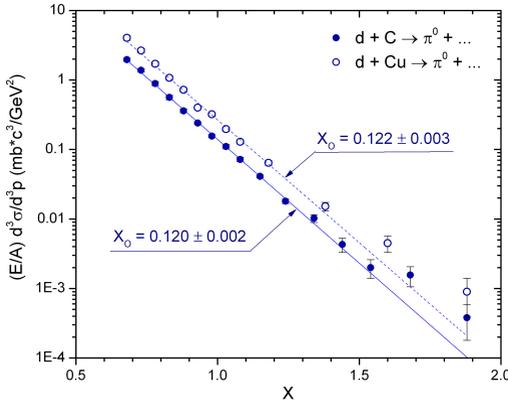
where  $N_\gamma$  is the number of  $\gamma$ -quanta (clusters) in the event,  $E_\gamma$  is the energy of  $\gamma$ -quanta,  $E_{\gamma\perp}$  is the transverse momentum of  $\gamma$ -quanta.  $1.4 \cdot 10^5$  events have been recorded on the DST, satisfying this criteria.

## 4 Inclusive $\pi^0$ production spectrum

In order to identify  $\pi^0$  mesons, all photon pair combinations are used to calculate the invariant mass in the each event. The combinatorial invariant mass spectra of the  $\gamma\gamma$  combinations, selected according to the criteria (1) ÷ (3) for the  $dC$  and  $dCu$  reactions, are shown in figure 1 (light color histograms). The dark color histograms in figure 1 represent the invariant mass distributions for  $\gamma\gamma$  combinations selected accidentally from different events. These combinatorial distributions, so-called "events mixing" were used to determine the background. The dashed line on the  $dC$  histogram indicates the invariant mass spectrum of  $\gamma\gamma$  pairs from a Monte Carlo simulation (for details, see [6]).



**Figure 1.** The combinatorial invariant mass spectra for the  $dC$  and  $dCu$  reactions.



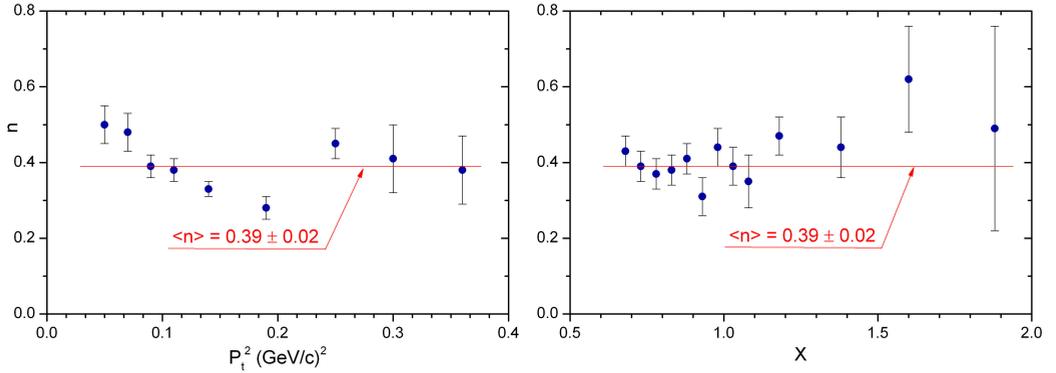
**Figure 2.** The invariant inclusive cross section of  $\pi^0$  mesons for deuterons at 4.5 GeV/c per nucleon on  $C$  and  $Cu$  targets averaged in the range  $\theta_\pi \leq 16^\circ$  and  $E_\pi \geq 2$  GeV versus the cumulative number  $X$ . It can be parameterized by an exponential form:  $Ed^3\sigma/d^3p \sim \exp(-X/X_0)$ . The experimental values of slope parameters  $X_0$ , that characterize the quark-parton structure function of the fragmenting nucleus [10], are  $0.120 \pm 0.002$  for  $C$  target and  $0.122 \pm 0.003$  for  $Cu$  target and approximately equal within the errors.

In figure 2 we present invariant inclusive cross section of  $\pi^0$  mesons for deuterons at 4.5 GeV/c per nucleon on  $C$  and  $Cu$  targets averaged in the range  $\theta_\pi \leq 16^\circ$  and  $E_\pi \geq 2$  GeV versus the cumulative number  $X$ . The  $X$  is determined by a minimum part of 4-momentum per nucleon in a fragmenting nucleus, necessary to pion production was kinematically allowed with the assumption that fragmentation occurs on one nucleon. It is equal to [3]:

$$X = \frac{P_r P_\pi - m_\pi^2/2}{(P_r P_f) - (P_f P_\pi) - m_N^2},$$

where  $P_r$  and  $P_f$  are four-momenta per nucleon of the nucleus, where fragmentation occurs and of the fragmented nucleus, respectively;  $m_N$  and  $m_\pi$  are the nucleon and pion mass;  $P_\pi$  is four-momenta of a pion. At the beam fragmentation (forward hemisphere) the formula becomes:

$$X = \frac{m_N E_\pi - m_\pi^2/2}{E_N m_N - E_N E_\pi - m_N^2 + P_N P_\pi \cos \theta_\pi},$$



**Figure 3.** The target dependence parameter  $n$  in the parameterization  $Ed^3\sigma/d^3p \sim A_t^n$  versus the transverse momenta  $P_T^2$  and the cumulative number  $X$  for the reactions  $d + A_i(C, Cu) \rightarrow \pi^0 + x$ .

where  $P_N, P_\pi, E_N, E_\pi$  are the nucleon and pion momentum and energy, respectively;  $\theta_\pi$  is the angle of pion emission (lab.system.).

We present the target dependence in the form  $Ed^3\sigma/d^3p \sim A_t^n$ , where  $A_t = 12$  and  $63.5$  is the nucleon number of the target. The dependence of the parameter  $n$  versus the transverse momenta  $P_T^2$  and the cumulative number  $X$  is shown in figure 3.

The parton models [8] predict that  $n$  is independent of  $X$  and  $P_T$  at large  $X$  and small  $P_T$ . According to these models, an incident hadron fragments when one of its constituent quarks collides in the target. The spectator quarks that escape collisions and thus retain their original fraction  $X$  of the projectile momentum can fragment or recombine with a slow quark ( $X \approx 0$ ) and form the large  $X$  and low  $P_T$  fragments. From the model we obtain a quantitative estimate  $n \approx 0.38$ , that is in good agreement with experimental data.

## 5 The double differential cross section

The double differential cross section of the reaction  $d + C \rightarrow \pi^0 + x$  is first measured at 4.5 GeV/c per nucleon using statistics of about  $4.5 \cdot 10^4 \pi^0$  mesons (figure 4, left).

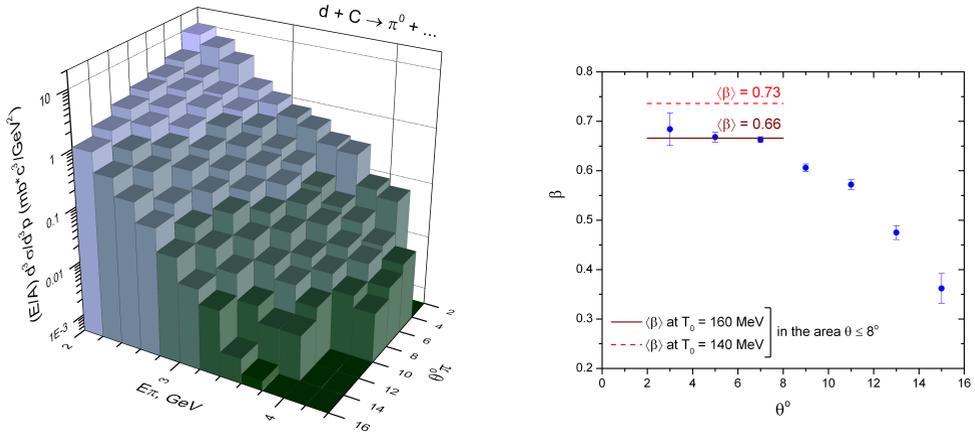
The invariant cross section of this reaction versus the energy  $E_\pi$  and the emission angle  $\theta_\pi$  of the  $\pi^0$  in the lab. syst. is analyzed at  $4^\circ \leq \theta_\pi \leq 16^\circ$  and  $2.0 \leq E_\pi \leq 4.7$  GeV.

We have obtained the slope parameters in the energy spectra  $Ed^3\sigma/d^3p (E_\pi, \theta_\pi\text{-fixed}) \sim \exp(-E/T(\theta_\pi))$ , for each interval of  $\theta_\pi$  and expressed  $T(\theta_\pi)$  as  $T(\theta_\pi) = T_0(1 - \beta^2)^{1/2}/(1 - \beta \cdot \cos \theta_\pi)$ .

Interpreting the parameter  $T_0 \sim m_\pi$  as the universal hadron temperature [11]:  $Ed^3\sigma/d^3p \sim \exp(-E^*/T_0)$ , we have obtained the values of  $\beta$ , the velocity of an intermediate cluster of nucleons which decays into a final pion (figure 4, right).

The obtained regularity of the  $\beta(\theta_\pi)$  in the interval  $\theta_\pi \leq 8^\circ$  qualitatively agrees with the predictions of the cluster models ( $\beta(\theta_\pi) \approx \text{const}$ ). However, for explanation of such small values of  $\beta$  one has to suppose second or more collisions in the target, which contradicts with observed target mass dependence.

Thus the obtained regularity of the  $\beta(\theta_\pi)$  indicates the absence of intermediate clusters (clusters of 2, 3,... nucleons formed in collisions of incident nucleon with nucleons in the target nuclei) responsible for pion production in above-mentioned kinematical region.



**Figure 4.** The invariant cross section  $\sigma_{inv} = (E/2)d^3\sigma/d^3p$  of the reaction  $d + C \rightarrow \pi^0 + x$  vs. the energy  $E$  and the emission angle  $\theta$  of  $\pi^0$  mesons (left), and the velocity  $\beta$  of a possible cluster vs. the emission angle  $\theta$  (right).

## 6 Comparisons with the data from another experiments

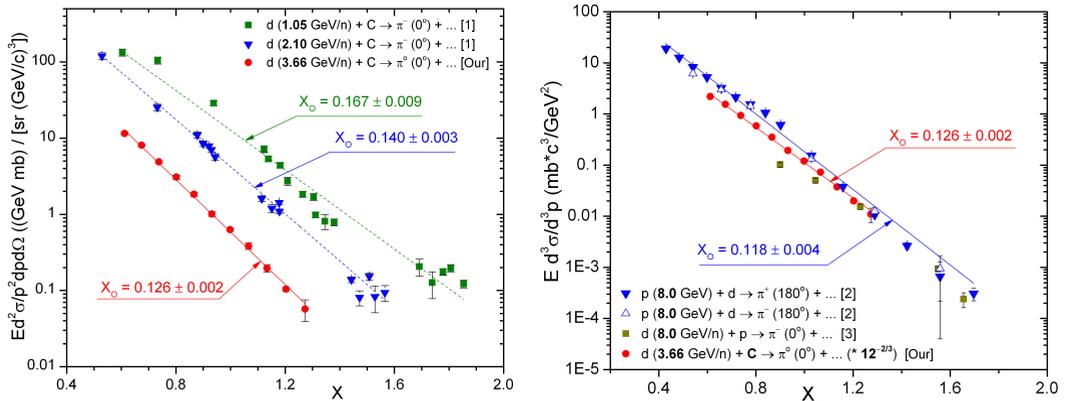
We have compared the invariant cross section obtained from our data for the reaction  $d + C \rightarrow \pi^0 + x$  with the data from another experiments on  $\pi^-$  production. For a more accurate comparison we made an extrapolation of our data to  $\theta_\pi = 0^\circ$  using results from the double differential cross section. In figure 5 (left) we present comparison with experiments, performed at the Bevalac of the Lawrence Berkeley Laboratory:  $d + C \rightarrow \pi^-(0^\circ) + x$  ( $P = 1.75$  and  $2.88$  GeV/c per nucleon) [1]. In figure 5 (right) we present comparison with experiments, performed at the LHE Synchrotron, Dubna:  $p + d \rightarrow \pi^-(180^\circ) + x$  and  $p + d \rightarrow \pi^+(180^\circ) + x$  ( $P = 8.9$  GeV/c, the DISK-2 setup) [2];  $d + p \rightarrow \pi^-(0^\circ) + x$  ( $P = 8.9$  GeV/c per nucleon, the SPHERE setup) [3]. In order to compare with proton data correctly, we have multiplied our data by  $A^{-2/3}$  ( $A = 12$ ). Parameter  $X_0$  in the parameterization  $(E/A_p)d^3\sigma/d^3p = A \exp(-X/X_0)$  have been extracted from all these data and shown in figure 6. The  $X_0$  decreases at lower momenta of beam, and almost reaches a plateau about a momentum of 4.5 GeV/c per nucleon.

## 7 Conclusion

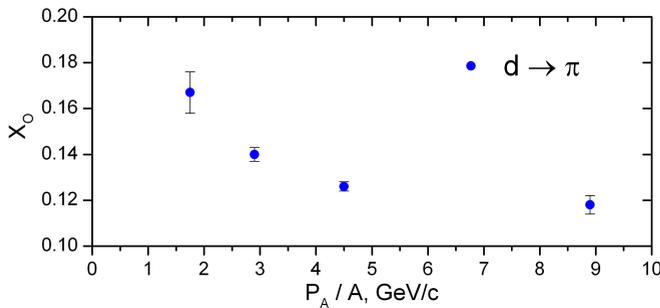
The invariant cross sections for the reactions  $d + A_i(^{12}\text{C}, ^{nat}\text{Cu}) \rightarrow \pi^0 + x$  were measured at the momentum 4.5 GeV/c per nucleon vs. cumulative number  $X$  within the range of  $0.6 \leq X \leq 2.0$ . The dependence of the cross sections on the mass of the target was presented in the form  $E d^3\sigma/d^3p \sim (A_i)^n$ . Exponent  $n = 0.39 \pm 0.02$  is independent on  $X$  within the kinematic region  $X > 0.6$ .

The predictions of the model of quark-parton recombination [8] are in good agreement with the observed A-dependence. The obtained regularity of the energy spectra of pions in different intervals of emission angles indicates the absence of intermediate clusters of nucleons [11], responsible for pion production in the kinematic region  $\theta_\pi \leq 16^\circ$  and  $E_\pi \geq 2.0$  GeV.

We carried out comparisons of the invariant cross section of the reaction  $d + C \rightarrow \pi^0 + x$ , extrapolated to  $\theta = 0^\circ$ , with the data from another experiments on  $\pi^-$  production. Parameter  $X_0$  in the parameterization  $(E/A_p)d^3\sigma/d^3p = A \exp(-X/X_0)$  decreases at lower momenta of beam, and almost reaches a plateau about a momentum of 4.5 GeV/c per nucleon.



**Figure 5.** Comparisons of our data with the data from the experiments, performed at the Bevalac of the Lawrence Berkeley Laboratory (left), and at the LHE Synchrophasotron, Dubna (right).



**Figure 6.** The slope parameter  $X_0$  vs. momenta of deuterons.

## References

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