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CUMULATIVE PION AND PROTON PRODUCTION IN *p–D* COLLISIONS AT 4.45 AND 8.9 GeV/c

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The new experimental data on momentum and angular dependencies of π^+-meson and proton production in *p—D* collision at incident proton momenta 4.45 and 8.9 (GeV/c) in the range $0.4 < X < 1.6$ were presented. The scaling behaviour of a cross section is investigated. The approximative factorization of cross section for the $p + D \to \pi^+ + \ldots$ process in the X, θ variables in cumulative range ($X > 1$) is found. The data are compared with theoretical calculations using the relativistic deuteron model.

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

Рождение кумулятивных пионов и протонов в *p–D* взаимодействиях при 4,45 и 8,9 ГэВ/с

Г.С.Аверичев и др.

Представлены новые экспериментальные данные по импульсным и угловым спектрам π^+-мезонов и протонов в *p—D* взаимодействиях при импульсах протона 4,45 и 8,9 (ГэВ/с) в области $x = 0{,}4$ 1,6. Изучен выход на скейлинговый режим и обнаружена приближенная факторизация сечений процесса $p + D \to \pi^+ + \ldots$ в кумулятивной области ($X > 1$) в переменных X и θ. Проведено сравнение полученных данных с расчетами, использующими модель релятивистского дейтрона.

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1. Introduction

The investigation of the inclusive pion and proton production in the *p–D* interactions in cumulative range is important to study mechanisms of particle production, a high momentum deuteron structure and search for transition pecularities from noncumulative to cumulative range. The data in this area can serve as the experimental test of various theoretical models using non-nucleon and quark degrees of freedom in nuclei.

We present a new experimental data on the momentum and angular dependencies of differential cross sections for the production of secondary pions and protons in *p–D* interactions at initial proton momenta 4.45 and 8.9 GeV/c both in noncumulative and cumulative ranges.

2. Experiment

The measurements of momentum spectra of a proton and a pion emitted in the interactions of a proton with deuteron nuclei have been performed at JINR Synchrophasotron by means of magnetic spectrometer DISC [1].

The 8.9 (Gev/c) and 4.45 (Gev/c) proton beam extracted from the accelerator with intensity up to ~ 10^{11} particles per pulse with pulse length of 0.4 s and repetition rate of 0.1 Hz fell on a cryogenic liquid deuterium target [2] with effective thickness about 1 (g/cm^2). The 96% part of the target is formed from the effective deuterium material and only 4% part is a material of target vessel. The time of work without adding of deuterium was more than 100 hours.

The angle, at which measurements have been made, was determined by the position of the magnetic-optical channel of the spectrometer consisted of an analyzing magnet and a doublet of quadrupole lenses. The secondary particles can be registered in the angular region 60° — 168°.

The angular acceptance of the spectrometer was determined by horizontal and vertical sizes of the scintillators of the first and last counters, respectively. The value of the acceptance was $4.35 \cdot 10^{-5}$ (sr).

The momenta of secondary particles were determined by the value of magnetic field in the gap of the analysing magnet. The measurements of spectra covered the momentum interval 0.15 — 1.6 (GeV/c). The momentum resolution of the spectrometer was about $\Delta p/p \cong 8.6\%$.

The secondary particles were separated by means of measurements of their momenta and two times of flight on the bases 3.8 m and 1 m with a time resolution 260 ps FWHM. Measurements of ionization losses into scintillator counters and intensity of Cherenkov light into hard radiator were carried out for higher separation of the detected secondary particles.

A relative intensity of beam particles was measured by two monitoring systems of scintillator counters. The calibration of the counters with accuracy ± (5 ÷ 7)% was made by measuring of the characteristic activities of ^{11}C produced in polystirol (C_8H_8) films exposed in the beam just upstream of the target.

The possible systematic uncertainty of the measured invariant cross section $Ed^3\sigma/dq^3$ is estimated to be about ± 15%.

3. Results and Discussion

The momentum spectra of π^+-meson produced at the angle $\theta_\pi = 168°$ and 180° in the interaction of the 8.9 (GeV/c) protons with deuteron target are shown in Fig.1. The data at angle $\theta_\pi = 180°$ are the results of our earlier measurements [3].

One can see these two sets of data are in good coincidence on the whole. A weak angular dependence of π^+-meson backward production means that in this region a contribution of rescattering mechanism is negligible and direct production mechanism is predominated. The solid curve is the calculation result of the invariant cross section in the

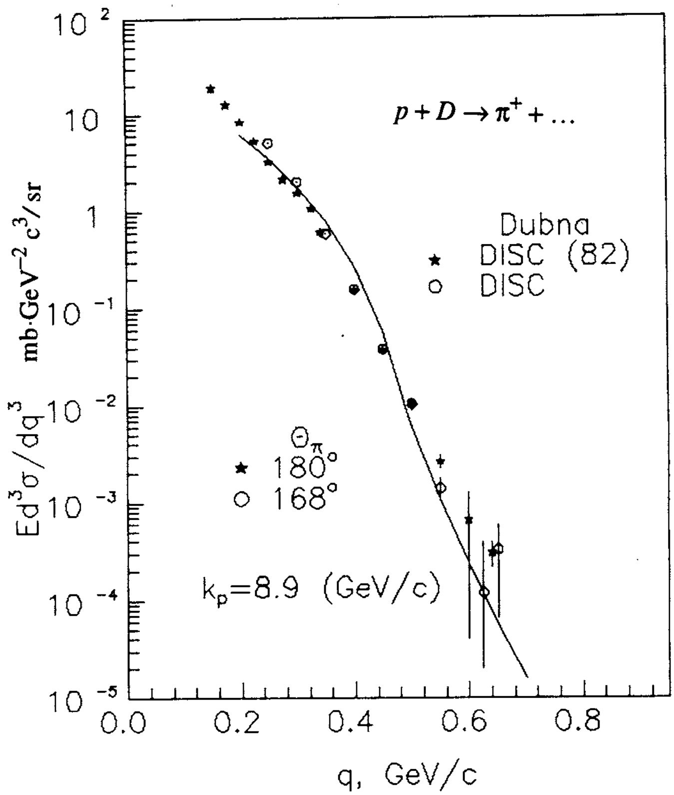

Fig.1. The dependence of the cross section of the $p + D \rightarrow \pi^+ + \ldots$ process on the pion momentum q for the initial proton momentum k_p = 8.9 (GeV/c) and pion scattering angles θ_π = 168°, 180°. Experimental data: * — [3], o — this experiment. The solid line is the calculation result in the relativistic impulse approximation with RDWF [4]

covariant approach in the light-cone variables with the relativistic deuteron wave function (RDWF) [4]. It is seen that the curve is in good agreement with experimental data. This result is related with the fact that motion of the nuclear constituents is more intensive in cumulative range due to off-shell effect [4].

Figure 2 shows the dependence of the invariant π^+-meson production cross section on cumulative number X (Stavinsky variable [5]) at the angle $\theta_\pi = 168°$ and initial proton momenta $k_p = 4.45,\ 8.9$ (GeV/c). The physical sense of the variable is the minimal mass of a target (A), in unit nucleon mass, needed for production of particle h with the momentum q and emission angle θ_h in accordance with 4-momentum conservation law for the reaction $p + A \to h + \ldots$.

The variable X for the $p + D \to \pi + \ldots$ is defined as follows:

$$X = \frac{2\,(p_1 p_3) - m_3^2}{(p_1 p_2) - (p_2 p_3) - m_1 m_2}\,. \tag{1}$$

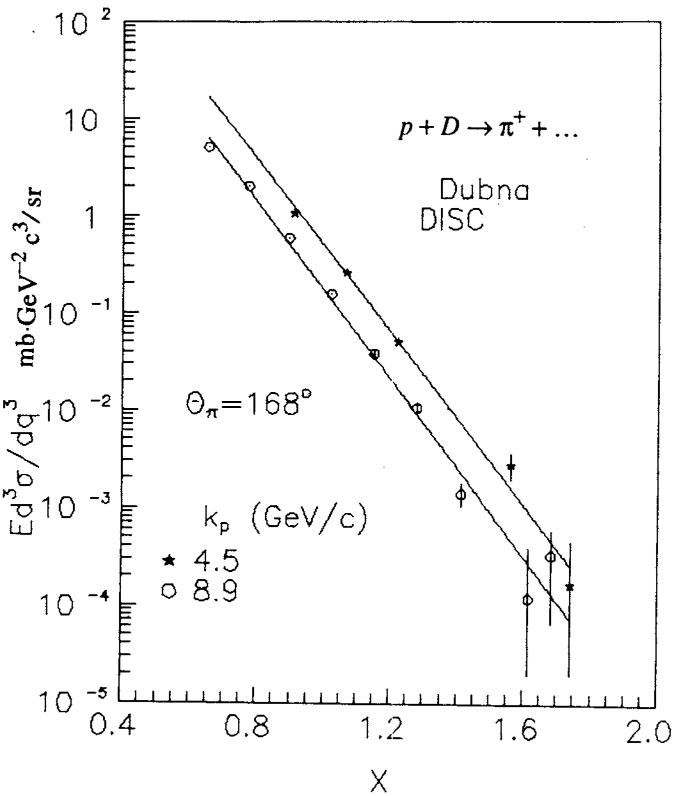

Fig.2. The dependence of the cross section of the $p + D \to \pi^+ (168°) + \ldots$ process on X for initial proton momenta $k_p = 4.45,\ 8.9$ (GeV/c). Solid lines are fits by the function $\sim \exp(-X/X_0)$

Here for the process $p+D \to \pi^{+}+\ldots$ the notations are used p_1, p_2, p_3 and $m_1 = m_N$, $m_2 = M$, $m_3 = m_\pi$ are 4-momenta and masses of proton, deuteron and pion, respectively.

The solid curves represent the results of the approximation spectra by function $\sim \exp - X/X_0$ for $X > 0.9$. The values of slope parameters are $X_0^{-1} = 10.2 \pm 1.4$ and 10.5 ± 0.98, respectively. The equality of slope parameters indicates that a scaling behaviour takes place already at 4.45 (GeV/c). It confirms that the contribution of rescattering mechanism is negligible here and a shape of the π^{+}-meson momentum spectrum is only determined by the reaction mechanism — a direct pion production. For middle and heavy nuclei the scaling behaviour of cross sections in Stavinsky variable X was observed at initial proton momentum 8.9 (GeV/c) and the asymptotic slope parameter value was found to be $X_0^{-1} \cong 7.14$ [6, 7, 8].

The momentum spectra of pion detected at angles $\theta_\pi = 90°$, 120°, 168° in *p–D* collisions at initial proton momentum 4.45 (GeV/c) are shown in Fig.3. Figure 4 shows the

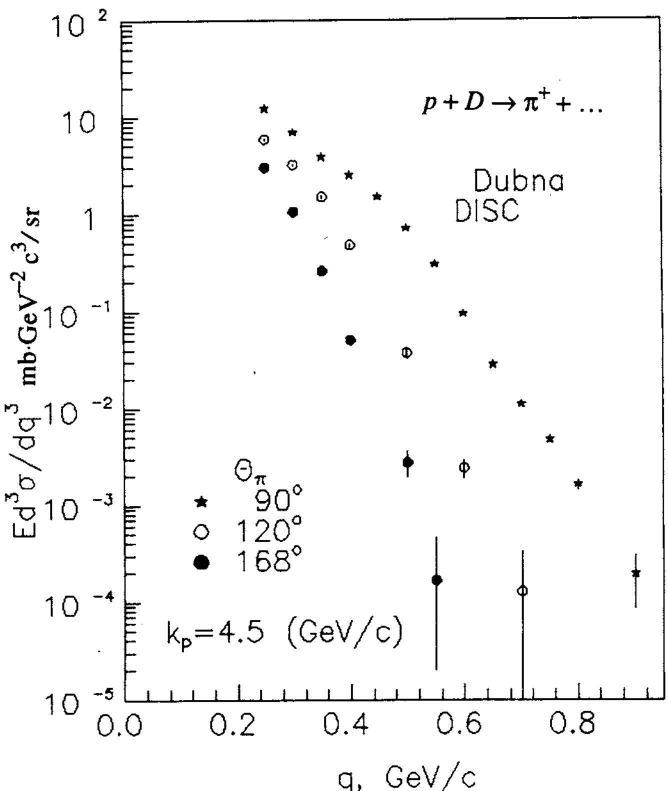

Fig.3. The dependence of the cross section of the $p+D \to \pi^{+}+\ldots$ process on the pion momentum q for the initial proton momentum $k_p = 4.45$ (GeV/c) and pion scattering angles $\theta_\pi = 90°$, 120°, 168°

same data in dependence on X. The hard part of spectra ($X > 1$) has been approximated by the function $\sim \exp(-X/X_0)$ and it was founded that the slope parameters are $X_0^{-1} = 9.5 \pm 1.9$ (90°), 10.0 ± 1.6 (120°) and 10.2 ± 1.4 (168°), respectively. One can see that the slope parameters determined at different angles are equal.

The ratios of cross sections at the same $X > 1$ for angles $\theta_\pi = 90°$, 168° and 120°, 168° are equal to 0.084 ± 0.048 and 0.45 ± 0.14, respectively. We should note that the similar results have been obtained for the heavy nuclei based on the mutual analysis of experimental data in cumulative range for scattering angles $\theta_\pi = 90°$, 168° [9] and 120° [10,11].

The cross section of the pion production in the hard part can be presented in the form $Ed^3\sigma/dq^3 = C f_1(X) f_2(\theta)$, where the dependence on the reaction mechanism comes to a factor $f_1(X)$.

It was shown in [12] on the basis of the hard scattering model that the shape of the spectrum on X is a universal one at different registration angles and a dependence of cross

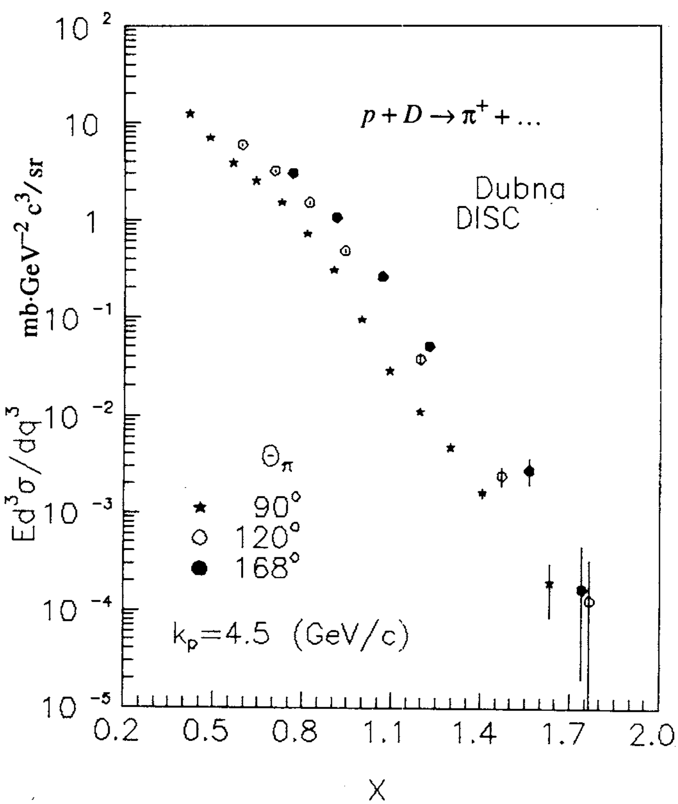

Fig.4. The dependence of the cross section of the $p + D \to \pi^+ + \ldots$ process on X for the initial proton momentum $k_p = 4.45$ (GeV/c) and pion scattering angles $\theta_\pi = 90°$, 120°, 168°

section on the angle is included in the factor $f_2(\theta) \approx (\sin(\theta/2))^8$. Therefore the cross section ratio at the same X and different θ does not depend on X. The ratios are equal to $\cong 0.06$ and $\cong 0.3$ for $\theta_\pi = 168°$, $90°$ and $168°$, $119°$, respectively. The results are quite close to the experimental values.

Figure 5 shows the dependence of the experimental data on cumulative number X for the $p + D \to \pi^+ + \ldots$ process at $k_p = 4.45$ (GeV/c) and $\theta_\pi = 90°$. The solid line is the result of the background approximation by $\sim \exp(-X/X_0)$ in cumulative range. One can see some bump at about $X \cong 0.8$. Figure 6 shows the data without the background. One can consider that the bump is due to the resonance Δ-production. It should be noted that the relative contribution of resonance mechanism decreases with increasing incident proton momentum k_p and scattering angle θ_π.

Figure 7 shows the inclusive cross section data for the $p + D \to p + \ldots$ process at momenta $k_p = 4.45$, 8.9 (GeV/c) and scattering angles $\theta_p = 90°$, $168°$. The experimental data [5] for the $D + p \to p(0°) + \ldots$ process at the deuteron momentum $k_d = 8.9$ (GeV/c) are

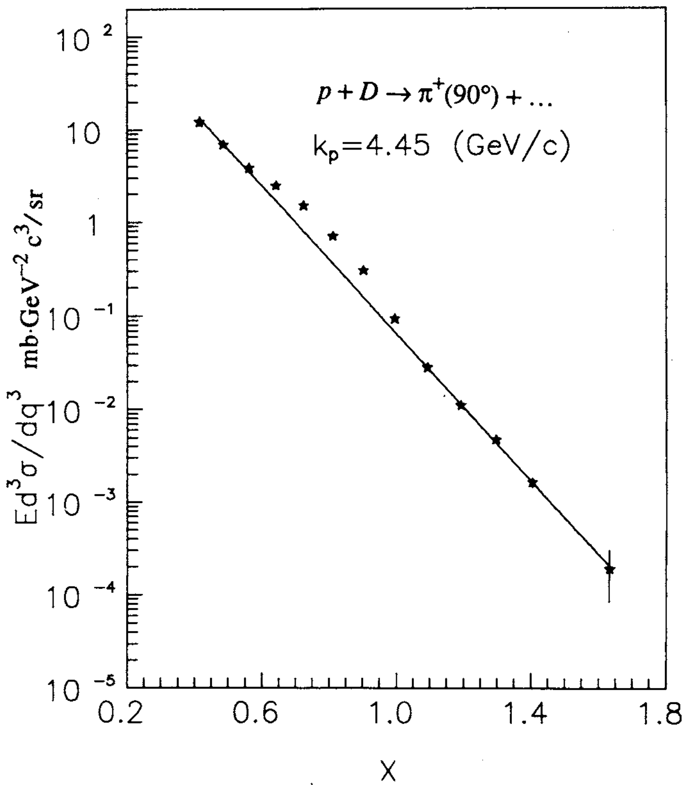

Fig.5. The distribution for π^+-meson production on X in the p–D collisions at $k_p = 4.45$ (GeV/c) and $\theta_\pi = 90°$

shown, too. One can see that our data at $\theta_p = 168°$ are in good agreement with the data [13] in the range $0.3 < q < 0.5$ (GeV/c). It should note that some difference may be near the kinematical boundary. The momentum q_{max} for the $p + D \to p + \ldots$ process varies from 0.55 (GeV/c) to 0.62 (GeV/c) with increasing proton momentum from $k_p = 4.45$ (GeV/c) to 8.9 (GeV/c). The coincidence of the data at $k_p = 4.45$ (GeV/c) and 8.9 (GeV/c) confirms the suggestion on the scaling behaviour of the cross section far from the kinematical boundary.

It is known that the spectator mechanism dominates for the backward proton production and the cross section is proportional to the square of a deuteron wave function

$$E\frac{d^3\sigma}{dq^3} \propto \Psi_d^2(\vec{q}^{\,2}) \qquad (2)$$

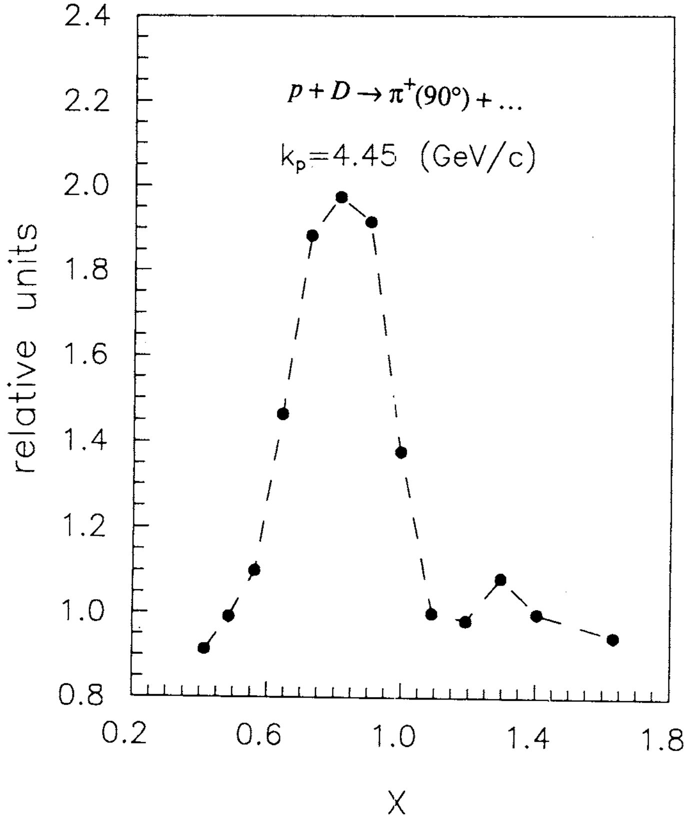

Fig.6. The dependence of the cross section to the background ratio on X for π^+-meson production in the p—D collisions at $k_p =$ = 4.5 (GeV/c) and $\theta_\pi = 90°$

The calculation results of cross section in the relativistic impulse approximation with RDWF [4], including only spectator mechanism at angles θ_p = 90°, 168°, 180°, are shown by solid lines in Fig. 7.

One can see that a good agreement of calculation results with the data at θ_p = 168°, 180° is observed excepting the range q = 0.25–0.4 (GeV/c) of the shoulder. It is known that the shoulder is connected with a resonance pion enhancement mechanism [14, 15]. The data for θ_p = 90° are inconsistent with calculation results in the range q < 0.7 (GeV/c). It means

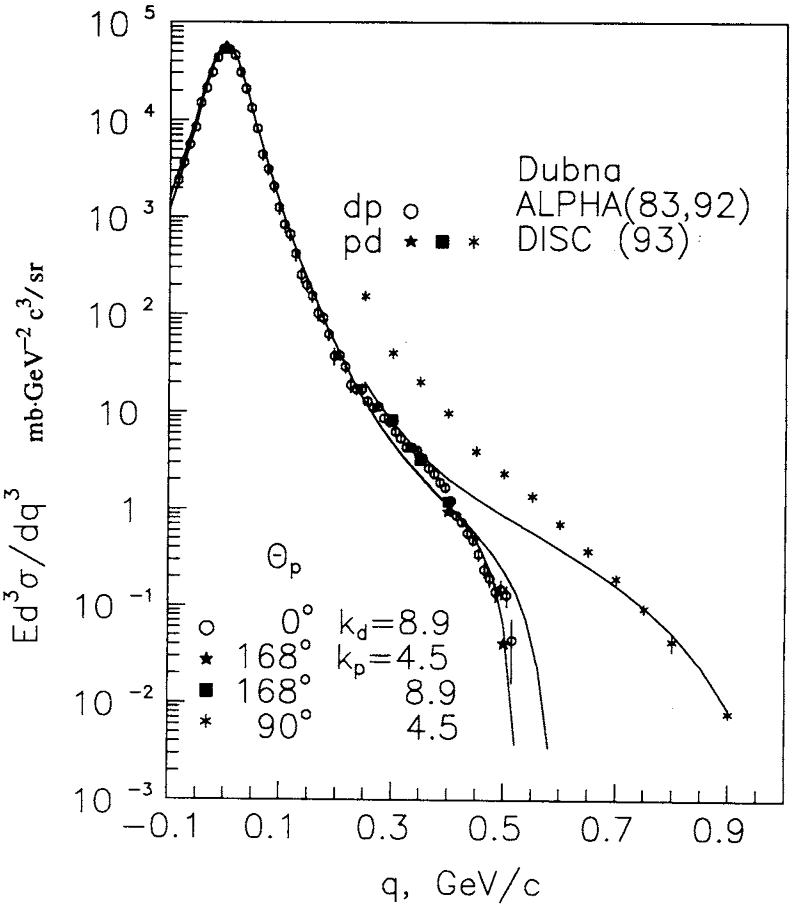

Fig.7. The momentum distribution for proton production in the p–D collision (the initial proton momentum k_p = 4.5 (GeV/c) and the proton scattering angles θ_p = 90°, 168° and k_p = 8.9 (GeV/c), θ_p = 168°) and D–p collision (the initial deuteron momentum k_d = 8.9 (GeV/c) and the proton scattering angles θ_p = 0°). Experimental data: o — [13], *, ●, ∗ — this experiment. Solid lines are calculations of spectator mechanism contribution to the cross section in the relativistic impulse approximation with RDWF [4]

that other mechanisms such as a hard scattering and direct fragmentation are essential [16] at the range. The spectator mechanism dominates at $\theta_p = 90°$ and $q > 0.7$ (GeV/c).

Conclusions

The new experimental data on pion and proton cross section production in the interactions of protons with initial momenta 4.45 (GeV/c) and 8.9 (GeV/c) with deuteron at detection angles 90° and 168° are presented.

The scaling asymptotic behaviour of the cross sections (slope parameter) for the secondary pion production on deuteron in the cumulative region ($X > 1$) is observed already at the initial proton momentum $k_p = 4.45$ (GeV/c).

The approximative factorization of cross sections for pion production on deuteron in variables X and θ in the hard part of spectrum is observed. The mean value of the slope parameter X_0^{-1} is found to be 9.9 ± 0.9.

The shoulder in the pion cross section at $\theta_\pi = 90°$ and $k_p = 4.45$ (GeV/c) in the region $0.5 < X < 1.0$ is observed. We consider it can be connected with the Δ-isobar production.

The comparison of the measured proton spectrum in the $p + D \to p\ (90°) + \ldots$ process with the calculation in the relativistic impulse approximation was made. It is shown that the spectator mechanism dominates in the hard part $q > 0.7$ (GeV/c) and non-spectator one is essential in the soft part of spectrum $q < 0.7$ (GeV/c).

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