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PRODUCTION OF CUMULATIVE PARTICLES AND QUARK-GLUON STRINGS MODEL

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1. Introduction

The production of particles in hadron-nucleus and nucleus-nucleus collisions in the kinematical region forbidden for the interactions of hadrons with free nucleons (the so called cumulative processes) is one of the main sources of information about the nuclear structure function. This kinematical region corresponds to the Feynman variable $x_F > 1$ (with respect to a single nucleon cluster) what from the parton model point of view corresponds to fragmentation of an object heavier than the nucleon. The cumulative phenomena were discovered in early seventies and were intensively investigated during last twenty years [1]. Usually this phenomena are considered in the initial energy region where the production cross section became approximately constant (in the region of the so-called nuclear scaling).

One of the most striking phenomenon here is the production of cumulative K^--mesons and antiprotons, i.e. those particles which contain no nuclear valence quarks in their structure. The ratio of the yield of this particles to ones which contain the nuclear valence quarks (e.g. K^-/K^+ or $\overline{p}/\pi^-$) experimentally became constant in the region $x_F > 1$ in contrast with quick decrease of the ratio on hydrogen when $x_F \to 1$. This phenomenon has no explanation in any model where nucleus is made of nucleons.

Now there are many theoretical models used for a description of these phenomena [2, 3]. All these models can be divided into "hot" and "cold" ones [4] i.e.,the models in which the massive object is created by an incident hadron [5-7] (due to either the multiple rescattering and "charge-exchange" or due to a fireball formation, etc.) and the models assuming the existence of such objects as an inherent property of the nuclear structure. [1] The latter are considered as a fluctuations of the nuclear mater density originally proposed by D.I.Blokhintsev [8] for the explanation of intensive nuclear fragment knockout and the production of high momentum backward protons [9, 10]. They are regarded now either as a multiquark configurations [11-14] or as a few-*nucleon correlations* [14, 15]. *The distinction of these two objects is in* different average momentum fraction carried by quarks. For the latter it has to be equal to that of nucleon[16].

As a main experiment allowing one to distinguish between these two big classes of models one may think of the deep inelastic scattering of leptons on nuclei in the region of the Bjorken variable $x_B > 1$. It is because the Bjorken variable can be interpreted as a minimal target mass in the nucleon mass units and because the lepton can "see" only the structure already existing in a nucleus.

In the framework of "cold" models the production of cumulative particles in the fragmentation processes of nuclei can be considered as the fragmentation of such a massive object in the nucleus into hadrons. One can hope that the mechanism of this fragmentation is similar to that in the nucleon-nucleon interactions which is well described by the quark-gluon string model (QGSM) [17, 18] based on the 1/N expansion in QCD [19] and on the theory of super-critical Pomeron [20]. This model gives a unified approach to processes of the elastic hadron scattering and to the multiple production of particles at high energies [17, 18]. The parameters of the Pomeron are determined from the analysis of data on the elastic scattering and total cross sections at high energies [17, 18]. Experimental data on the multiplicity distributions of charged particles and inclusive spectra of pions, kaons, baryons (p,n,Λ) and the corresponding antibaryons were **satisfactorily** described in Ref.[17, 18, 20, 21].

In this paper we try to apply this approach to the analysis of the cumulative hadrons produced in the processes of the nuclei fragmentation assuming the existence of some multiquark configurations in nuclei. Let us stress that this approach differs from the one used in

[1] Note however that in many respects the interpretation depends on the frame of the reference. The above classificaton assumes the nucleus rest frame.

[23] first of all by the physical content of quark distribution. The quark distribution used in [16] really was the quark distribution in nuclei measured in the deep inelastic process and sharing with the gluon distribution the total momenta of nuclei. While the quark distribution of QGSM going to be used here is the quark distribution of the ends of strings. In Sec. 2 the general formalism of the QGSM is outlined and its application to the multiquark states is considered. In Sec. 3 the results of calculation are given and are discussed. Sec. 4 is reserved for further discussion and for conclusions.

2.General Formalism

Let us consider the $pA \to h'X$ reaction in the reference frame where the nucleus A moves with a large energy. We assume as in ref.[23] that this nucleus is made of A usual nucleons with some probability w_1 and of a 3k- quark colorless clusters with some probability w_k where k changes from 2 to A. In the framework of the QGSM [17, 18] the main contribution to the inclusive spectra of hadrons h' in the processes $pN \to h'X$ is due to the s-channel multi-cylinder type graphs , corresponding to the production of n-Pomeron jets or 2n-chains (Fig.1). Usually the planar diagrams corresponding to Reggeon exchanges in the t-channel are neglected at high energies because they decrease as $1/\sqrt{s}$ with the increase of the initial energy [17, 18]. Therefore we shall confine ourselves by the analysis of multi-cylinder type graphs only.

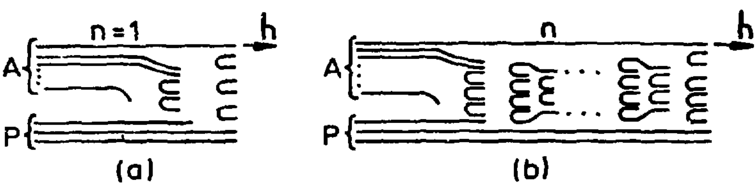


Figure 1: a)"Cut-cylinder" graph in the s-channel of $Ap \to hX$ processes, b) production of n-Pomeron showers or $2n$ $q\bar{q}$ chains in this reaction.

The inclusive spectrum of hadrons h' in the discussed reaction $pA \rightarrow h'X$ integrated over transverse momenta p_t can be written in the form analogous to the case of the process $pN \rightarrow h'X$,i. e. in the following form [17, 18]:

$$\varrho_A(x) = \int E\frac{d\sigma_A}{d^3p}d^3p = \sum_{n=1}\sigma_n(s)\varphi_n(x);\ \varphi_n(x) = F^n_{qq}(x) + F^n_{q_v}(x) + \tag{1}$$
$$+2(n-1)F^n_{q_{sea}}(x),$$

where σ_n is the cross section of the 2n-chains production corresponding to the s-channel discontinuity of the multi-cylinder (multi-Pomeron) diagrams: $x = p'/p_{max}$ where p' is the momentum of the cumulative hadron produced in $pA \rightarrow h'X$ reaction and p_{max} is the maximum momentum of the hadron h' produced in $pN \rightarrow h'X$ processes. The cross section σ_n can be calculated in the framework of the so-called quasi-eikonal approximation [22]. The functions $F^n_\tau(x)$, where the subscript τ means either the valence quark or diquark or see quark, have the following form:

$$F^n_\tau(x) = \int_x^A f^n_\tau(x')G_{\tau\rightarrow h'}(x/x')dx', \tag{2}$$

here $G_{\tau\rightarrow h'}(z) = zD_{\tau\rightarrow h'}(z)$, $D_{\tau\rightarrow h'}(z)$ is the fragmentation function of the quark (antiquark, diquark) into the hadron h'; $f^n_\tau(x')$ is the distribution of quarks (antiquarks or diquarks) at the ends of the quark-gluon strings as the function of x'. According to the hypothesis about the existence of the mentioned above multiquark configurations in the nucleus [11-14], the function $f^n_\tau(x)$ can be written in the following form

[23] :

$$f^n_T(x) = \sum_{k=1}^{A} w_k f^n_{T,k}(x), \tag{3}$$

Here $f^n_{T,k}(x)$ is the quark distribution in the k-nucleon cluster, it is normalized by the following condition:

$$\int_o^k f^n_{T,k}(x)dx = k. \tag{4}$$

Hadron production from the fragmentation of the nucleus A in the kinematical region forbidden for collision of the initial proton with free nucleon can be considered in the infinite momentum frame. The configuration of the nuclear wave function is formed before the collision of the nucleus A with the proton. The fast final hadron h' produced by the fragmentation of the k-cluster can have the maximal fraction of momentum $x = k$.

Further turn now to the quark distribution of a k-cluster $f^n_{T,k}(x)$ in the framework of the QGSM [17, 18]. Consider first a cluster with k=2. The probability to slow one 3q-system with the momentum fraction x_{3q} is proportional [17, 18] to $g_1 = {x_{3q}}^{2(1-\overline{\alpha_B(0)})}$, where $\overline{\alpha_B(0)}$ is the intercept of the average baryon Regge trajectory, $\overline{\alpha_B(0)} = -0.5 - 0.0$ [17, 18]. But the probability to slow one diquark with the momentum fraction x_{qq}, according to [22] is proportional to $g_2 = x_{qq}^{(1+\alpha_R(0)-2\overline{\alpha_B(0)})}$, where $\alpha_R(0) = 0.5$ is the intercept of the boson (ϱ, f, A_2, π) Regge trajectory. Then the probability to slow $3q$-system and diquark in the cluster with $k = 2$ is equal to $g = g_1 g_2$. Note that $x_{3q} + x_{qq} + x = 2$, where x is the momentum fraction of the fast quark in the considered $6q$ cluster and its maximal value is equal to 2, as mentioned above. Therefore integrating the function g over x_{qq} we have for $g(x)$: $g(x) = (2-x)^{3-2\overline{\alpha}_B(0)+b_N}$, where for $n = 1$ $b_N = \alpha_R(0) - 2\overline{\alpha}_B(0)$ and for any n $b_{N,n} = \alpha_R(0) - 2\overline{\alpha}_B(0) + n - 1$ (see [20, 21]). Further, in order to get the distribution function $f^n_{T,k=2}(x)$ it is necessary to divide this probability g(x) by (2-x) and to take into account the Regge behaviour of $f^n_{T,k=2}(x)$ at $x \to 0$ (see [20, 22]). So the normalized quark distribution $f^n_{T,k=2}(x)$ will have the following form:

$$f^n_{T,k=2}(x) = C_2 g(x) f^n_{T,N}(x) = C_2 x^{-\alpha_R(0)}(2-x)^{2(1-\overline{\alpha}_B(0))+b_N}. \tag{5}$$

The coefficient C_2 can be found from the normalization condition (4).

For the case of a 3k-cluster the quark distribution $f^n_{\tau,k}(x)$ will be proportional to the probability to slow (k-1) 3q-clusters and one diquark. Finally we have for $f^n_\tau(x)$ the following expression:

$$f^n_{\tau,k}(x) = C_k x^{-\alpha_R(0)}(k-x)^{2(1-\bar{\alpha}_B(0))(k-1)+b_N}. \tag{6}$$

Consider now the problem of the calculation of the probabilities w_k of the existence of k-nucleon clusters in the nucleus. We calculate these values approximately using the so-called "flucton" model [8], [11-14]. It was suggested in [8] the existence of some coherent states containing k nucleons in the rest frame of a nucleus. The volume of this coherence, according to [8], is bounded by the sphere of the volume V_c with the radius r_c. Then the expression for the probability w_k of the existence of the k-cluster in A can be written in the following form [4] :

$$w_k = C^A_{k-1}\int (V_c\rho(r))^{k-1}(1-V_c\rho(r))^{A-(k-1)}d^3r/V_0, \tag{7}$$

where $\rho(r)$ is the nuclear density normalized by the following manner

$$\int \rho(r)d^3r = 1. \tag{8}$$

$$C^A_{k-1} = \frac{A(A-1)...(A-(k-1)+1)}{(k-1)!}. \tag{9}$$

Here $(V_c\rho(r))^{k-1}$ is the probability that k nucleons are contained in the coherent volume V_c; the expression $(1-V_c\rho(r))^{A-(k-1)}$ is the probability that others (A-k) nucleons are not contained in this volume. Using formula (8) the A-dependence of w_k can be obtained. For example, for the constant nuclear density C ($C = 1/AV_0$), where V_0 is the volume of the nucleon, we have the following form for w_k :

$$w_k = \frac{A(A-1)...(A-(k-1)+1)}{(k-1)!V_0}\int \frac{(V_c/V_0)^{k-1}}{A^{k-1}} \times (1-\frac{(V_c/V_0)}{A})^{A-k+1} d^3r; \tag{10}$$

for A≫k we have approximately:

$$w_k \simeq \frac{A^{k-1}}{(k-1)!} \times \frac{(V_c/V_0)^{k-1}}{A^{k-1}} \times exp(-V_c/V_0)\int d^3r \sim A. \tag{11}$$

So we assume that eq.(3) written in the rest frame of deuteron can be used **for calculation of ω_k in eq.(3).**

Consider now the problem of the choice of the fragmentation functions (FF) of quarks into hadron h' $D_{r-h'}(z)$. We shall assume that they don't depend on the projectile, i.e that the partons fragment outside the nucleus and therefore we can take these functions as in the case of the process $pp \to h'X$ [24] and [25, 26]. However it turned out that the FF presented in [26] can describe well enough the experimental data on the ratio R_1 of inclusive spectra of K^+- and K^--mesons produced in p-p collisions [25] at large $x > 0.5$. This ratio calculated in the framework of the QGSM [17, 18] with FF from [26] are presented in Fig.2. This figure shows the distinction between the results of the calculation and the experimental data at $x_F > 0.5$, where x_F is Feynman variable. Therefore we have tried to choose new parameters of the FF (see Appendix) in order to describe both the ratio and the inclusive spectra of cumulative K^+- and K^--mesons produced in p-A collisions.

3. Results and Discussions

We calculated the inclusive spectra of cumulative particles: $\pi^\pm$, $K^\pm$- mesons and antiprotons ($\bar{p}$) using the expressions (1). For the calculation of the distribution of quarks in the nucleus it is necessary to know two parameters: the radius of the coherent quark state r_c and the value $\overline{\alpha}_B$ (see formula (5)) which are contained in the expression for the probability to slow down (k-1) 3q-clusters. This value has been found earier [23] from the description of the deuteron fragmentation on protons, it was found to be equal to $\overline{\alpha}_B(0) = -0.05 \div -0.1$. The value of another parameter r_c is found in this paper from the best description of the experimental data on the inclusive spectra of both $\pi^\pm$ and $K^\pm$-mesons. I was found to be $r_c = 0.65$ fm. As it was mentioned above the FF of quarks into $K^\pm$-mesons presented in [26] don't allow to describe the experimental data on the ratio R_1 of the inclusive spectra of K^+- and K^--mesons at large x, i.e., $x > 0.5$. Therefore we have found new parameters of the FF (see Appendix) from the fit of R_1 and experimental data about the inclusive spectra of cumulative $\pi^\pm$- and $K^\pm$ -mesons. Experimental data on this ratio R_1 from ref.[27], our fit with new parameters in FF and the calculation of the R_1 according to ref. [24] are presented in Fig.2. It is seen from this figure that the ratio $R_1 = K^+/K^-$ in p-p collision has the strong dependence on x at $x < 0.5$ ($\sim (1-x)^{-3}$) and a weaker one at larger x , $x > 0.5$ ($\sim (1-x)^{(1\div 1.5)}$, see the full curve on Fig.2). It is caused by more hard behaviour of the distribution of sea quarks at the ends of the quark-gluon string than those which fit the sea quarks structure function in a deep inelastic lepton-nucleon scattering.

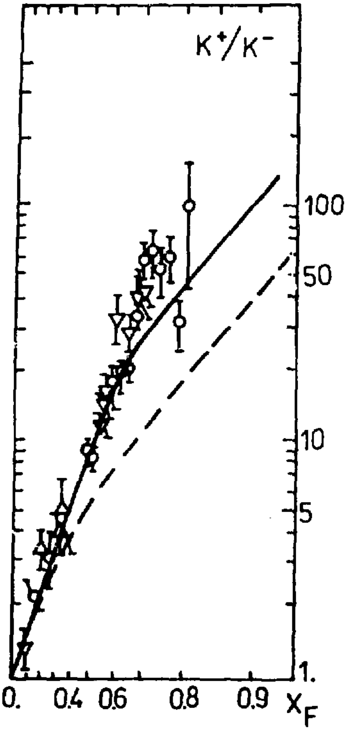


Figure 2: The ratio of the inclusive spectra of K^+ and K^- mesons produced in p-p collision; o - at $\sqrt{s} = 45(Gev.)$, $p_t = 0.6(Gev/c)$, ∇ - at $\sqrt{s}$=45 Gev/c, p_t=0.8 Gev/c, Δ - at $\sqrt{s}$=31 Gev/c,p_t=0.4 GeV/c. Full curve is our calculation result with new parameters in FF a_k=0.02,a_{2k}=20 (see Appendix); dashed curve is the calculations according to ref.[26].

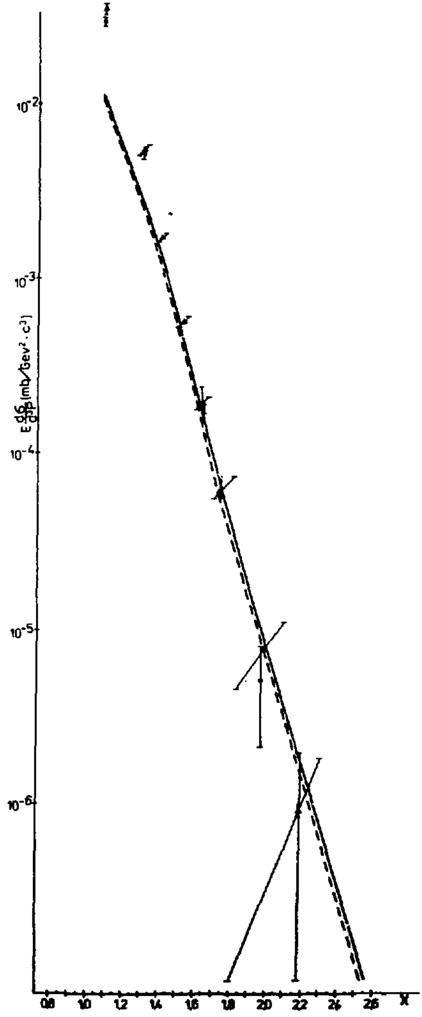


Figure 3: The inclusive spectra of cumulative π^+ (full curve) and π^- (dashed one) produced in p-Be collision at initial energy E_0=44 Gev and $\theta_\pi = 159°$; experimental data are taken from ref.[28], $\circ - \pi^+$, $\triangle - \pi^-$-mesons.

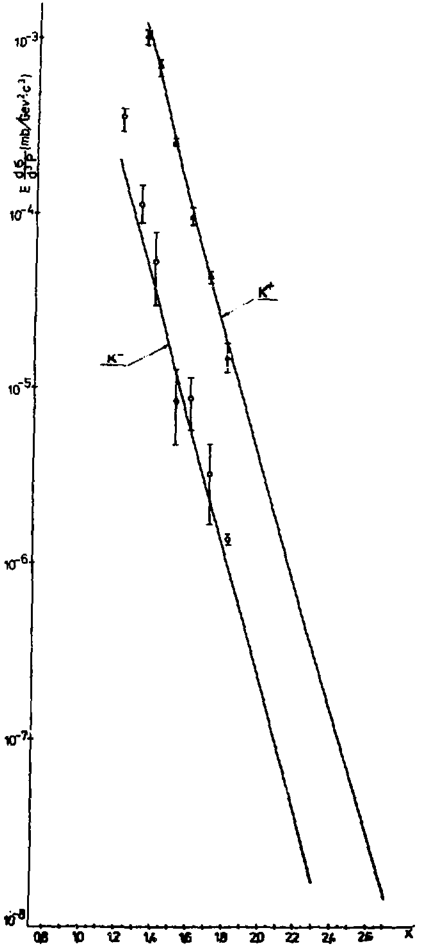


Figure 4: The inclusive spectra of cumulative $K^{\pm}$-mesons produced in p-Be collision at E_0=40 GeV, $\theta_K = 159°$. Experimental data are taken from ref.[29].

Now we will discuss the calculation results. The inclusive spectra of cumulative π- and K-mesons produced in p-A collisions and corresponding experimental data at $E_0 \simeq 40$ GeV [28, 29] are presented in Figs.3,4 which demonstrate the satisfactory description of the experimental data. The ratios of the inclusive spectra of K^+, K^- ($R_2 = K^+/K^-$) and π^-, K^- ($R_3 = \pi^-/K^-$) and corresponding experimental data [28, 29] are presented in Fig.5. It demonstrates the satisfactory agreement of the calculations with the experimental data also. The question arrises why the ratio R_2 (see Fig.4a) increases more slowly with the increase of x, than in the case of K-mesons production on free nucleon, i.e. for $pN \to K^{\pm}X$. The reason is the following. The sea quark distribution in the QGSM differs from that of valence quarks in the limit $x \to 1$ only by one extra power of $1 - x$ for the proton-proton scattering case (see fig.1 and the expression for b_N with $n \geq 2$). For the scattering with k-nucleon flucton this difference is relatively much weaker due to larger of power $k - x$ itself. Of course a quick enough decrease of w_k as k increases is also important for the x-behaviour of this ratio.

Consider now the production of cumulative antiprotons in p-A collisions. We can apply our approach to the calculation of the inclusive spectra of cumulative antiprotons produced by the nucleus fragmentation. However there are no experimental data on such spectra at the production angle $\theta_{\overline{p}} \simeq 180°$ in the rest frame of the nucleus (or zero angle in the frame of moving nucleus). There are the experimental data at $\theta_{\overline{p}} \approx 90° - 110°$ only [29] what corresponds to a large p_T. However the QGSM can be applied to the cumulative particles production only in the region of small p_T. Hard quark collisions which have to give a dominant contribution at large p_T to the inclusive spectra of antiprotons are not taken into account in our approach. We do not know definitely however where the change of the regime will happen. So it is interesting to compare our calculation with existing experimental data on the antiprotons production which have $p_T < 1$ Gev. This comparison for the ratio of the inclusive spectra of $\overline{p}$- and K^--mesons ($R_4 = \overline{P}/K^-$) is presented in Fig.6. One can see that model can explain the order of magnitude of antiprotons production also. That could be considered as an indication to a small contribution of the hard scattering mechanism in this region. It is interesting to note that in contrast to R_2 and R_3 the ratio R_4 increases with x. This is a prediction of our model.

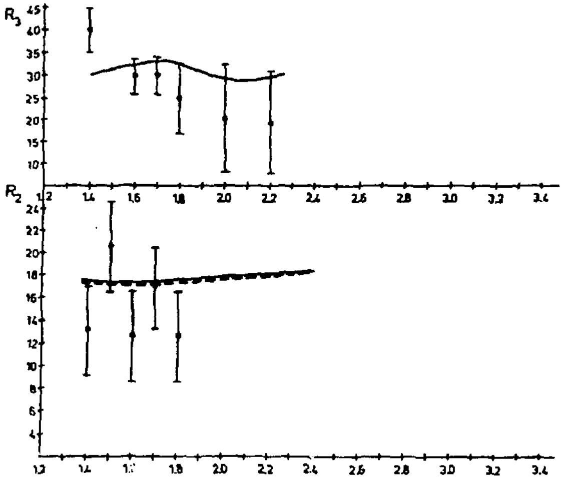
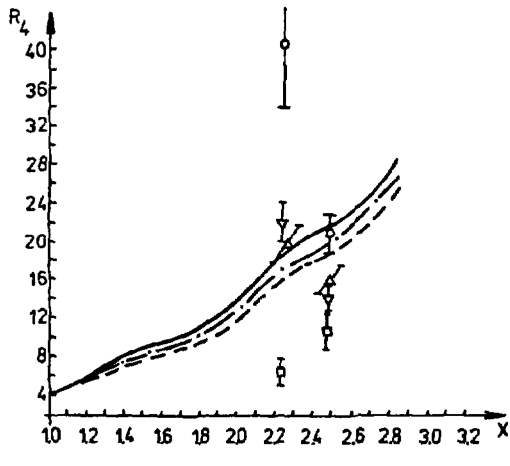


Figure 5: The ratio of cumulative: a) K^+ and K^--mesons ($R_2 = K^+/K^-$), full curve is the result of calculation with r_c=0.65 fm, dashed one is the same with r_c=0.5 fm. b) the ratio of π^- and K^--mesons ($R_3 = \pi^-/K^-$) as the function of x. Experimental data are taken from ref.[28, 29]



4. Conclusion

In this paper we have suggested a new approach to the description of the cumulative particle production based on the QGSM. This model gives a rather successful description of the fragmentation phenomena of usual hadrons. We have made the assumption on the existence of heavy multiquark states inside the fragmenting nucleus. The main problem here was in the explanat'on of the production of cumulative particles like K^- and $\overline{p}$ which consist of the seq quarks of the fragmenting nucleus where an astonishing phenomenon was experimentally discovered: the ratio of the yields of such particles to those which contain nuclear valence quarks (π, K^+, p) are independent of x at $x > 1$ and are rather large. It is in contrast to the sharp decrease of this ratio in the fragmentation of nucleons ($x < 1$). Such behaviour can not be understood in the framework of the simplest fragmentation models which use valence and seq quark distributions measured in deep inelastic scattering and in any model of nuclei made of nucleons. The reason for this is a fast decrease of the seq quark distribution in nucleons compared with the valence one. This difference is much smaller for the QGSM. The main result of this paper is in the demonstration that the difference is small enough in order to obtain the approximately constant behaviour of the ratio K^+/K^- without coming into contradiction with experimental data about this ratio in the nucleon-nucleon scattering. We also predict a growth of $K^-/\overline{p}$ which could be checked in future experiments.

Note once more that quark distributions over x used in QGSM and in this paper are the distributions at the ends of each quark-gluon string. These quarl. distributions differ therefore from the correspondent quark structure functions obtained in the deep inelastic scattering. It is interesting to study a connection between the quark distributions used here and the quark and gluon distributions functions seen in deep inelastic scattering. We plan to consider this problem somewhere also.

Figure 6: The ratio of cumulative K^--mesons and antiprotons $\overline{p}$ ($R_4 = K^-/\overline{p}$) produced in p-A collision at E_0=10 GeV, $\theta_h \doteq 180^\circ$ as the function of x. Curves: the full is for Ta (exper. points-$\triangle$) the dotted-dashed is for Al (exper. points-$\bullet$) the dashed is for Be (exper. points-o); exper. points-$\triangle$ are for Cu Experimental data are taken from ref.[29] at E_0= 10 GeV and $\theta_h = 119^\circ$

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5. Appendix

Consider firstly the fragmentation function (FF). Their form was taken as in [23, 24], but some parameters were changed. In particular the coefficients a_k, a_{2k} in FF $D_{s\to K^-(z)}$, $D_{uu\to K^+(z)}$, $D_{u\to K^+(z)}$, $D_{ud\to K^+(z)}$, $D_{u\to K^-(z)}$, $D_{uu\to K^-(z)}$, $D_{ud\to K^-(z)}$, were changed. These FF , according to [24], have the following forms:

$$D_{s\to K^-(z)} = \frac{1}{z}[b_k z^{1-\alpha_\varphi(0)} * (1-z)^{-\alpha_R(0)+\lambda} + a_k(1-z)^{-\alpha_R(0)+\lambda+2(1-\alpha_\varphi(0))}]$$

$$D_{\bar{s}\to K^+(z)} = D_{s\to K^-(z)} \tag{12}$$

$$D_{uu\to K^+(z)} = \frac{a_k}{z}(1-z)^{\alpha_R(0)-2\alpha_N(0)+\lambda+\delta}(1 + a_{2k}z) \tag{13}$$

$$D_{u\to K^+(z)} = \frac{a_k}{z}(1-z)^{-alpha_\varphi(0)+\lambda}(1 + a_{1k}z)/z \tag{14}$$

$$D_{ud\to K^+(z)} = \frac{a_k}{z}(1-z)^{2\alpha_R(0)-\alpha_\varphi(0)-2\alpha_N(0)+\delta}\left(1 + a_{1k}z + \frac{1}{z}(1-z)^2\right) \tag{15}$$

$$D_{u\to K^-(z)} = \frac{a_k}{z}(1-z)^{-\alpha_\varphi(0)+\lambda+1} \tag{16}$$

$$D_{uu\to K^-(z)} = \frac{a_k}{z}(1-z)^{\alpha_R(0)-2\alpha_N(0)+\lambda+\delta} \tag{17}$$

$$D_{ud\to K^-(z)} = \frac{a_k}{z}(1-z)^{-\alpha_\varphi(0)-2\alpha_N(0)+\lambda+2}\left(\frac{1}{2} + \frac{(1-z)}{2}\right) \tag{18}$$

were $\delta = \alpha_R(0) - \alpha_\varphi(0) \approx 0.5$

In this paper the values of a_k,a_{2k} were chosen as the following:

$$a_k = 0.02 \text{ (instead 0.05 of ref.[24])}$$

$$a_{2k} = 20 \text{ (instead 5 of ref.[24])}.$$

Other parameters in FF (A.1)-(A.7) are taken as in [24].

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