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Ξ^0 PRODUCTION BY HIGH ENERGY PROTONS ON NUCLEI AND QUARK FRAGMENTATION FUNCTIONS

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Data on inclusive Ξ^0 production by 400 GeV protons incident on Be and Pb nuclei is used to extract quark and diquark fragmentation functions. The forward ($x \gtrsim 0.5$) Ξ^0 production from wounded quarks is small, but changing its estimate well within errors, one changes the expected single spectator quark fragmentation function by a large factor. This effect, unnoticed in previous analyses, leaves the spectator diquark fragmentation function as our only reliable estimate. This function is similar to the proton into K^+ fragmentation function and to the valence quark in the proton structure function, but very different from the proton diquark into Λ fragmentation function. Data is consistent with the assumption that the two quarks in the diquark fragment independently, but the experimental errors are too large to make a strong statement.

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1. Introduction

In recent years much work has been devoted to the description of low-p_t hadronic fragmentation in terms of elementary hadronic constituents. As it has been stressed many times such a description enables one to obtain from high-energy hadron-hadron experiments information concerning the behaviour of quarks in soft hadronic collisions. The possibility of using soft hadron-nucleus collisions for the study of quark fragmentation into hadrons was discussed in Ref. [1]. The authors of Ref. [1] have proposed a method based on the additive quark model (AQM), which allows a determination of the fragmentation functions of quarks from the A dependence of the inclusive spectra. This method was applied to spectra of K^0_s and Λ produced in 300 GeV proton-nucleus collisions [1]. In the present paper we calculate quark fragmentation functions into Ξ^0 using the data on Ξ^0 production in proton-beryl and proton-lead interactions at 400 GeV [2] and compare our results with the results of Ref. [1]. We show that direct recombination of spectator quarks plays an important role in the production of fast strange particles.

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2. *Additive quark model and fast particle production in hadron-nucleus interactions*

In AQM hadrons are considered as bound states of quarks. In soft hadronic processes quarks cannot be identified with bare quarks seen in hard processes. They are instead dressed quarks (valons). The assumption of quark additivity in hadron-hadron collisions enables one to consider hadron-nucleus collisions in terms of nearly independent interactions of the quarks (we ignore here diffraction dissociation processes). In general, when a proton hits a nucleus of atomic number A, three diffrent situations may occur coresponding to the possible fates of the three quarks of the projectile:

(*i*) one quark of the projectile proton interacts (gets wounded) and the remaining two do not interact we shall call them diquark spectator,

(*ii*) two quarks of the projectile get wounded and one is spectator,

(*iii*) three quarks get wounded.

The probability of these configurations $P_i(A)$ can be obtained applying Glauber's model of multiple scattering [3] assuming that quarks interact with nucleons of nuclei with a cross section $\sigma_{\rm in}^{\rm qN} = 1/3\sigma_{\rm in}^{\rm pN}$. In this approach the single particle inclusive spectrum of produced hadrons $n_A^{\rm h}(x)$ is parametrized as follows:

$$n_A^{\rm h}(x) = \sum_{i=1}^{3} P_i(A) n_i^{\rm h}(x, A). \tag{1}$$

(We limit our discussion to particles produced at $p_t = 0$). Here $n_i^{\rm h}(x, A)$ is the fragmentation function of the system of i wounded and 3-i spectator quarks. Some qualitative features of the fragmentation functions $n_i(x, A)$ for x large seem to be well established by experiment. The absence of intra-nuclear cascading of fast secondaries implies that fast secondary hadrons are created outside the nucleus [4]. The validity of the parametrization for particle production in the "plateau region" proposed in [5] suggests that production of particles in this region does not depend on how many times the wounded quarks have interacted inside the nucleus. According to these two observations, the fragmentation functions for x large (say, $x > 0.3$) become independent of nuclear size:

$$n_i^{\rm h}(x, A) \xrightarrow{x \text{ large}} n_i^{\rm h}(x). \tag{2}$$

Assuming independent production of particles from the wounded quarks one can go futher writing down the fragmentation functions of quark systems as the sums of fragmentation functions describing production of particles from wounded quarks and from spectator quarks separately:

$$\begin{aligned} n_1^{\rm h}(x) &= n_{\rm d}^{\rm h}(x) + n_{\rm w}^{\rm h}(x), \\ n_2^{\rm h}(x) &= n_{\rm s}^{\rm h}(x) + 2n_{\rm w}^{\rm h}(x), \\ n_3^{\rm h}(x) &= 3n_{\rm w}^{\rm h}(x). \end{aligned} \tag{3}$$

Substituting (3) into (1) we get:

$$n_A^{\rm h}(x) = P_1(A) n_{\rm d}^{\rm h}(x) + P_2(A) n_{\rm s}^{\rm h}(x) + w_A n_{\rm w}^{\rm h}(x), \tag{4}$$

where $n_d^h(x)$ is the fragmentation function of a diquark spectator, $n_s^h(x)$ is the fragmentation function of a quark spectator and $n_w^h(x)$ is the fragmentation function of a wounded quark. Formula (4) was introduced in [1] and applied to K_s^0 and Λ spectrum in pBe, pCu and pPb collisions. Since the authors of Ref. [1] had data for three nuclei, they were able to derive quark fragmentation functions solving the system of the three linear equations (4) written for Pb, Cu, Be.

3. Ξ^0 production from spectator and wounded quarks

The data for Ξ^0 production in pBe and pPb interaction [2] are insufficient to derive quark fragmentation functions — we need information concerning the production of Ξ^0 on a third nucleus. We applied here the parametrization widely used for inclusive particle production on nuclei

$$n_A^h(x) = C_h A^{\alpha_h(x)}. \tag{5}$$

We tested this formula fitting the Λ inclusive multiplicity in pCu collisions to the prediction based on formula (5) with parameters C_Λ and α_Λ obtained from pBe and pPb data. The

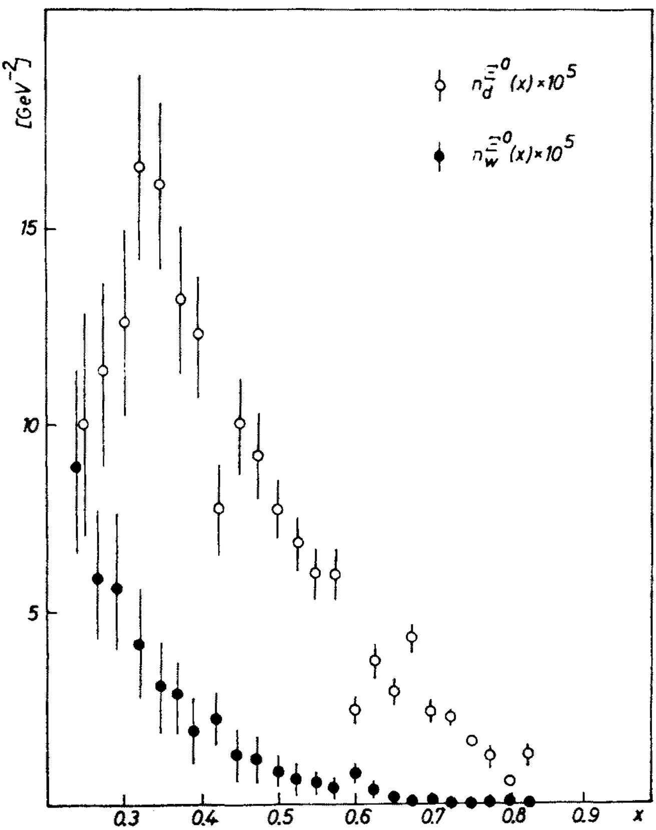

Fig. 1. The $n_d^{\Xi^0}$ and $n_w^{\Xi^0}$ fragmentation functions

χ^2 was 30.5 for 24 degrees of freedom. We assumed that this parametrization is valid also for the Ξ^0 inclusive spectrum and derived C_{Ξ^0} and $\alpha_{\Xi^0}(x)$ using the pBe and pPb data. With C_{Ξ^0} and $\alpha_{\Xi^0}(x)$ we were able to calculate the inclusive spectrum of Ξ^0 for arbitrary nuclei. We chose the Cu nucleus for further analysis. As a next step we calculated the quark fragmentation functions solving the system of three linear equations (4) written for Pb, Cu and Be nuclei. The $P_i(A)$ and w_A functions were taken from [1]. The elements of the matrix:

$$B(x) = A^{-1}\sigma^2(x)A^{-1^{\mathrm{T}}}, \tag{6}$$

where: $A = \begin{pmatrix} P_1(\mathrm{Pb}) & P_2(\mathrm{Pb}) & w_{\mathrm{Pb}} \\ P_1(\mathrm{Cu}) & P_2(\mathrm{Cu}) & w_{\mathrm{Cu}} \\ P_1(\mathrm{Be}) & P_2(\mathrm{Be}) & w_{\mathrm{Be}} \end{pmatrix}$ and $\sigma^2(x)$ is the variance and covariance matrix of $n^{\mathrm{h}}_{\mathrm{Cu}}(x)$, $n^{\mathrm{h}}_{\mathrm{Pb}}(x)$, $n^{\mathrm{h}}_{\mathrm{Be}}(x)$, describe their correlations. In Fig. 1 the quark fragmentation functions derived from the data are plotted versus scaled Feynman momentum. One sees that the fragmentation function of the diquark spectator $n^{\Xi^0}_{\mathrm{d}}$ is quite well determined from the data. The quark spectator fragmentation function $n^{\Xi^0}_{\mathrm{s}}$ cannot be reliably determined from the data and is not shown in Fig. 1. To obtain more information on $n^{\Xi^0}_{\mathrm{s}}$ we tried to fix $n^{\Xi^0}_{\mathrm{w}}$. In Fig. 2 we show the $n^{\Xi^0}_{\mathrm{s}}$ calculated assuming:

a) $n^{\Xi^0}_{\mathrm{w}}(x) = 0$ as in Ref. [1] for Λ production,

b) $n^{\Xi^0}_{\mathrm{w}}(x) = .0044(1-x)^{4.19}$. The parameters are taken to reproduce the $n^{\Xi^0}_{\mathrm{Cu}}$ as a sum of contributions from wounded and spectator quarks.

Both the $n^{\Xi^0}_{\mathrm{w}}$ functions, when substituted into (4) give good fits to the Ξ^0 production on Cu: $\chi^2 = 20.5$ and $\chi^2 = 7.4$ for 23 degrees of freedom. One can see that $n^{\Xi^0}_{\mathrm{s}}$ for the two choices of $n^{\Xi^0}_{\mathrm{w}}$ is dramatically different. The reason for this is that $n^{\Xi^0}_{\mathrm{s}}$ is strongly correlated to $n^{\Xi^0}_{\mathrm{w}}$. A more detailed analysis of the covariance matrix $B(x)$ and the estimates of $n^{\mathrm{h}}_{\mathrm{s}}$ for

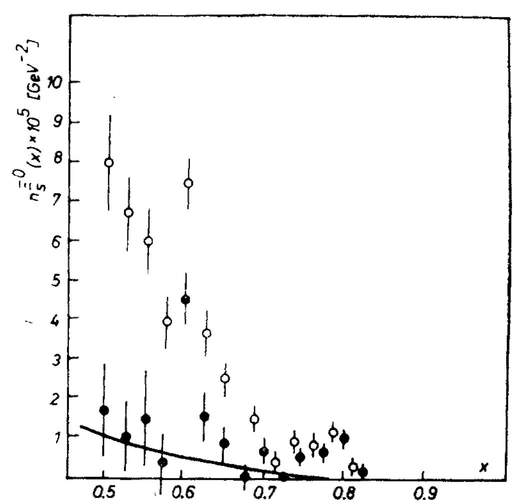

Fig. 2. The $n^{\Xi^0}_{\mathrm{s}}$ fragmentation functions calculated assuming: (a) $n^{\Xi^0}_{\mathrm{w}} = 0$ — ○, (b) $n^{\Xi^0}_{\mathrm{w}} = .0044(1-x)^{4.19}$ — ●. Shown is also the $n^{\Xi^0}_{\mathrm{w}} = .0044(1-x)^{4.19}$ curve

various nuclear targets can be found in Ref. [6]. Here we only point out that the accuracy of estimating n_s^h as compared to n_d^h and n_w^h is always very poor and, in particular, the n_s^Λ obtained in [1] is found to be unreliable.

4. The comparison of fragmentation functions of quarks into Ξ^0, Λ, K_s^0, K^+:

To compare our results with the results from Ref. [1] we show on Fig. 3 the fragmentation functions of diquark spectator into Λ, K_s^0 taken from [1] and the fragmentation function of diquark spectator into Ξ^0. In addition we show there the inclusive spectrum of K^+ production in pp interaction and valence quark inclusive spectrum. All functions are normalized to arbitrary units. One sees that the fragmentation function of diquark spectator into Ξ^0 does follow qualitatively the shape of the diquark $\rightarrow K_s^0$ fragmentation

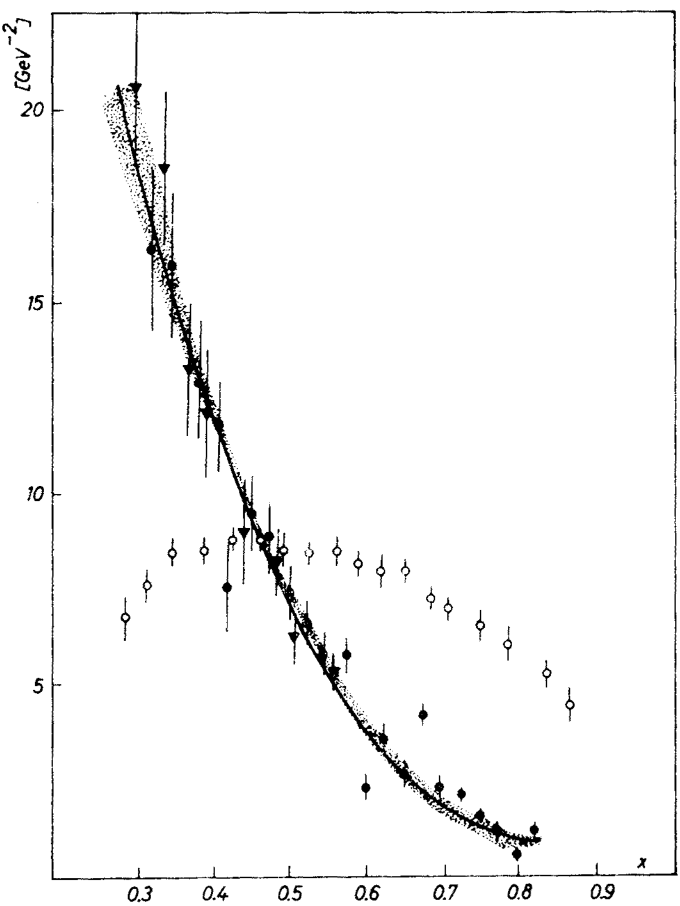

Fig. 3. The $n_d^{\Xi^0}$ — ●, n_d^Λ — ○, $n_d^{K_s^0}$ — ▼ fragmentation functions; the inclusive spectrum of K^+ production in pp interactions taken from Ref. [7] — shadowed area; the valence quark momentum distribution in proton taken from Ref. [1] — the full curve. All functions are normalized to arbitrary units

function and differs substantially from the diquark → Λ fragmentation function. The most natural interpretation of this observation is that the shape of the fragmentation function depends on how many quarks from the diquark can be found in the inclusively produced hadron. Let us consider at first Λ = (uds) production. In this case both quarks of the diquark can be found in the final state if a u quark did interact inside the nucleus. For Ξ^0 = (uss) and $K^0_s = 1/2[(d\bar{s})+(s\bar{d})]$ production only one quark from the diquark can be found in the final hadron: d quark in diquark → K^0_s fragmentation and u quark in diquark → Ξ^0 fragmentation.

A very interesting feature of the fragmentation functions of the diquark spectator into Ξ^0, K^0_s, K^+ is their similarity to the valence quark momentum distribution in a proton. We assumed that the fragmentation function of a diquark into K^+ is similar to the proton → K^+ fragmentation function, since fast K^+ production from a wounded quark is supposed to be small. This observation indicates that independent recombination of one of the quarks from the diquark spectator is an important source of fast Ξ^0, K^+ and K^0_s. The independence of quarks in diquark hypothesis can be easily checked in the case of Ξ^0 production. If the quarks act independently in Ξ^0 production the simple relation to be satisfied is:

$$n_s^{\Xi^0} = \tfrac{1}{2}\, n_d^{\Xi^0}. \tag{7}$$

The origin of this relation is that on the average there is two times more u quarks in a diquark than in a quark spectator. To test the validity of formula (7) we assumed a linear dependence between $n_s^{\Xi^0}$ and $n_d^{\Xi^0}$:

$$n_s^{\Xi^0} = \alpha n_d^{\Xi^0}. \tag{8}$$

Substituting (8) into (7) we have:

$$n_A^{\Xi^0}(x) = (P_1(A)+\alpha P_2 A)n_d(x)+w_A n_w(x). \tag{9}$$

It is seen that the Pb and Be data are sufficient to find n_d and n_w as functions of parameter α. The $n_d^{\Xi^0}(x, \alpha)$ and $n_s^{\Xi^0}(x, \alpha)$ obtained in this way enable one to give prediction of the AQM

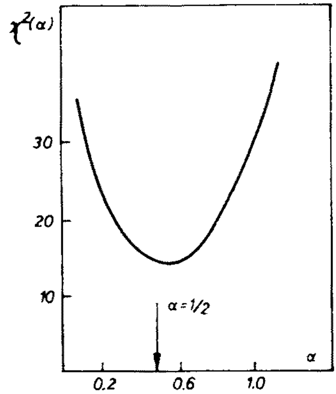

Fig. 4. The $\chi^2(\alpha)$ of the fit to $n_{Cu}^{\Xi^0}(x)$ multiplicity for 24 degrees of freedom

supported by independence hypothesis for the Ξ^0 production in the pCu interaction for arbitrary α. To check which value of α gives the best fit to $n_{\text{Cu}}^{\Xi^0}(x)$ obtained in Chapter 3 we calculated the χ^2 of the fit as a function of α. The behaviour of $\chi^2(\alpha)$ is shown in Fig. 4. The minimum near $\alpha = 1/2$ supports the hypothesis, but one cannot exclude the values of α in a broad region around the minimum of χ^2. To summarize, the data for Ξ^0, K_s^0, K^+ production is giving an evidence that the Ξ^0, K_s^0, K^+ production is indeed dominated by independent recombination of each quark of the diquark spectator.

Finally, let us add one remark. The three parameter formula (4) used in our analysis can be tested only if precise measurement of inclusive hadron production on at least four nuclei is available. We feel, however, that the simple rules for the Ξ^0, K_s^0, K^+ and Λ production observed at the level of interacting and fragmentating quarks enable one to accept our results as evidence for the applicability of the AQM to soft hadron-nucleus interactions.

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