DISTRIBUTIONS OF LEADING BARYONS IN CONSTITUENT QUARK MODELS*

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High energy proton and antiproton scattering on nuclei is considered. Inclusive spectra $p^{\pm}A \to p^{\pm} + X$ are discussed in the framework of constituent quark models. Predictions of the models with colour excitations of constituent quarks are examined. These models in which fragmentation into leading hadrons depends only on the total colour of the constituents in the intermediate state are excluded by the experimental data.

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1. Introduction

The unique phenomenological description of the high energy hadron-nucleus interactions at low p_t has not been achieved yet. In particular the question is still open if in scattering on nuclei one can observe some new effects which are rare or do not appear at all in the inelastic scattering on single nucleons. During the last several years the experimental and theoretical studies have been concentrated mainly on central nucleus-nucleus interactions and searches for the signals of the quark-gluon plasma. A compelling reason for this is that multiple interactions and large interaction volumes which are provided by the nucleus-nucleus collisions may help to reveal some new exotic phenomena. On the other hand, however, due to complexity of the process and the large number of nucleons involved it is not easy, if possible at all, to unravel the dynamics underlying the nucleus-nucleus interactions. In this respect the scattering of hadrons on nuclear targets is interesting because particle production in the forward direction originates from a relatively simple system (a single hadron) which is involved in the multiple scattering process. At the energies available at the

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present day accelerators the multiparticle production in nucleus-nucleus collisions is dominated by the fragmentations of the beam and the target nuclei. The contribution of central production is quite small, so, extrapolations towards higher (RHIC) energies are difficult. Once again a careful analysis of hadron-nucleus interactions can reduce a variety of the models describing the nucleus-nucleus reactions.

One of the crucial steps in building of the phenomenological models is to select these parameters which are most relevant for a quantitative description of the particle production in nuclear interactions. An obvious candidate could be the total number of the hadrons (nucleons) in the colliding systems. The data on hadron–nucleus interactions tell us, however, that at high energies the number of wounded nucleons in the nucleus, or equivalently the number of collisions ν between the hadron in the beam and the nucleons in the target nucleus is a much more relevant parameter. In fact the total multiplicity is to a good approximation a linear function of ν. A number of models has been proposed in which ν determines inclusive spectra in hadron-nucleus collisions. The dual parton model [1] is perhaps the best known example. The predictions of this model for the distributions of baryons can be found in [2].

The data on the total multiplicity does not preclude the possibility that the inclusive spectra can be described equally well or even better by phenomenological models using some other parameters instead of ν. In the constituent quark models [3–6] the number of wounded constituent quarks is assumed to be the most relevant quantity. Since the number of wounded constituent quarks in the nucleus is proportional to ν the total multiplicities predicted by these models also agree with the data. However, the inclusive spectra in the forward region are different in the constituent quark models and in the multiple scattering models [1, 2]. In [7] it has been noted that the colour configuration of the wounded constituent quarks may be also a relevant parameter. In general the particle production in the constituent quark model can depend on both the number of wounded constituents and their colour charges. A simple hypothesis is that the spectra of particles depend only on the total colour configuration of the fragmenting constituents [7].

In the present paper the constituent quark model with colour is examined. We use the existing data on the inclusive proton and antiproton spectra in the reactions:

$$pA \to p + X \tag{1}$$

$$\bar{p}A \to \bar{p} + X \tag{2}$$

of the ACCMOR [8] (the reactions 1 and 2, $E_{\text{beam}} = 120$ GeV) and the FNAL-SAS [9] (the reaction 1, $E_{\text{beam}} = 100$ GeV) experiments. For the ACCMOR data it is also possible to subtract the contributions of the baryon pair production and the target nucleus fragmentation from the inclusive spectra of protons and antiprotons. The subtracted inclusive spectra of the leading protons and antiprotons are closely related to the fragmentation of the projectiles.

The paper is organized as follows. In Section 2 the general assumptions and predictions of the constituent quark model are presented including colour degrees of freedom. In Section 3 three versions of the model are discussed. Comparison with the experimental data is performed in Section 4. Our results are discussed and summarized in Section 5.

2. Constituent quark models

The general assumption of wounded quark models [3–6] is that the particle production in the projectile fragmentation region depends on the number of wounded constituents of the projectile. According to the modification of these models proposed in [7] the particle production depends on the total colour configuration of the constituent quarks in the projectile after the collision. The constituent quarks before and after the collision transform as colour triplets and constituent antiquarks as the complex conjugate representations. In the case of baryon interactions the three constituent quarks after the collision can carry the colour charge belonging to one of the representations in the expansion $3 \otimes 3 \otimes 3 = 1 \oplus 8 \oplus 8 \oplus 10$. The overall colour conservation allows for the singlet-singlet and the octet-octet configurations in the baryon-baryon inelastic scattering. In addition the decuplet-antidecuplet is possible in baryon-antibaryon collisions. This requires, however, wounding of at least two quarks and two antiquarks, and the probability of such an event in a single baryon-antibaryon collision is small. The configuration 10–10^* is also allowed in baryon-nucleus and antibaryon-nucleus interactions.

The intermediate colour configurations are neutralized in the process of fragmentation into hadrons. According to the model the functions describing the fragmentation of the projectile should depend only on the colour charge of the intermediate system. Thus, the proton interactions with nuclear targets are described by three fragmentation functions:

$$\frac{d\sigma}{dx}\Big|_{pA} = \sigma^1_{pA} F^1(x) + \sigma^8_{pA} F^8(x) + \sigma^{10}_{pA} F^{10}(x)\,, \tag{3}$$

where $F^i(x)$ denotes the fragmentation function of the colour state i and σ^i_{pA} are the production cross sections of the corresponding colour configurations. The contributions of the different colour states to the total inelastic cross section depend on further assumptions about the production mechanism. A few simple models will be presented in the next section. Before doing that, let us discuss qualitatively some expected features of the fragmentation functions for $p^{\pm}A$ interactions. The octet configuration should correspond to the pomeron exchange or at least it should give the dominant contribution. Thus in the region where diffractive dissociation can be neglected the corresponding fragmentation function should be similar to the distribution in the nucleon-nucleon interaction. It is also plausible that the singlet configuration leads to the diffractive-like excitation of the scattered particles. Then the corresponding fragmentation function should be appreciable for larger values of x, *i.e.* the singlet configuration is expected to fragment into fast baryons (antibaryons). It is difficult to build a baryon from three constituent quarks in the decuplet state which is completely symmetric in colour. The constituents can neutralize their colour by creation of three $q\bar{q}$ pairs and this leads to fragmentation into three mesons. If this is the dominant fragmentation mechanism it results in the transfer of the baryon number into the target fragmentation region. The same is true for the fragmentation into an antibaryon of three constituent antiquarks in 10^* configuration. This leads to a new mechanism of baryon number annihilation because antiquarks which are slow in the target fragmentation region can be bound in mesons together with the constituent quarks from the nucleus. Thus, one expect in p^+A scattering a soft component in the baryon spectra due to 10-10^* configuration. For p^-A this component should be suppressed at small x.

3. Production of the intermediate colour states

The relative probabilities of the different colour configurations depend on the mechanism of colour exchange in the constituent-constituent scattering at small p_t. In the present paper only the projectile $p^{\pm}$ fragmentation is considered. For the sake of simplicity we describe the interactions between a given constituent q in the projectile and the constituents in a given nucleon N in the nucleus A of the target as some effective colour exchange process. For the fixed impact parameter b the probability of this process

$$\hat{\sigma}_{qN}(b) = \hat{\sigma}^1_{qN}(b) + \hat{\sigma}^8_{qN}(b) \tag{4}$$

is given by the sum of the two possible colour exchange processes: singlet and octet exchange. In Eq. (4)

$$\hat{\sigma}^i_{qN} = \sigma^i_{qN} \int dz\, \rho_A(b,z) = \sigma^i_{qN}\, T(b) \qquad (i = 1, 8)\,, \tag{5}$$

and $\rho_A(b,z)$ denotes the nuclear density distribution in the nucleus A. Multiple scattering in the constituent-nucleon collision is neglected, so, in this approximation the nucleon-nucleon cross section is given by

$$\hat{\sigma}_{NN}(b) = 3\hat{\sigma}_{qN}(b)\,. \tag{6}$$

After integration over the impact parameter b the following formula is obtained for the inelastic nucleon-nucleus cross section

$$\sigma_{inel} = \int d^2b \left[1 - (1 - \hat{\sigma}_{NN})^A\right] . \tag{7}$$

The cross sections σ^i_{qN} depend on the details of the interaction mechanism. In the following we consider two extreme assumptions:

- (Model I) after scattering the probabilities of different colour configurations are given by statistical weights. If only one quark is wounded the singlet or the octet of colour are produced with relative probabilities 1/9 and 8/9. If more then one quark is wounded the three colour configurations are possible with probabilities 1/27 for the singlet, 16/27 for the octet and 10/27 for the decuplet.
- (Model II) the constituent can effectively emit or absorb only octet or singlet of colour in the collision with a single nucleon. The probabilities of producing different intermediate colour states depend on the number of collisions between the constituents and the nucleons in the nucleus A.

In Model I the A-dependence of the contributions to the total cross section is determined by the probability of wounding one quark in the projectile. In this version of the model the contributions of 1 and 8 configurations decrease with A whereas the contributions of 10 in p^+A and 10^* in p^-A inelastic collisions increase with A. This is illustrated in Fig.1.

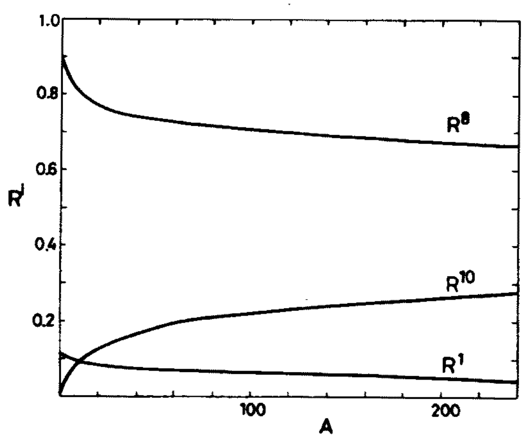

Fig. 1. The relative contributions of the different colour configurations to the inelastic cross section $p^{\pm}A$ in the Model I.

In [7] the formula for the cross section of the decuplet intermediate state in Model II has been derived. Following [7] we have derived formulae for the production cross sections of the all possible intermediate colour states in the models under consideration:

$$\sigma^1_{BA} = \frac{1}{27} \int d^2b \left[1 + 20 \left(1 - \frac{27}{8}\hat{\sigma}^8_{qN}\right)^A + 6 \left(1 - \frac{9}{4}\hat{\sigma}^8_{qN}\right)^A - 27 \left(1 - 3\hat{\sigma}^8_{qN} - 3\hat{\sigma}^1_{qN}\right)^A \right], \tag{8}$$

$$\sigma^8_{BA} = \frac{8}{27} \int d^2b \left[2 - 5 \left(1 - \frac{27}{8}\hat{\sigma}^8_{qN}\right)^A + 3 \left(1 - \frac{9}{4}\hat{\sigma}^8_{qN}\right)^A \right], \tag{9}$$

$$\sigma^{10}_{BA} = \frac{10}{27} \int d^2b \left[1 + 2 \left(1 - \frac{27}{8}\hat{\sigma}^8_{qN}\right)^A - 3 \left(1 - \frac{9}{4}\hat{\sigma}^8_{qN}\right)^A \right]. \tag{10}$$

After summation over the intermediate colour configurations one derives the formula (7) for the inelastic hadron-nucleus cross section.

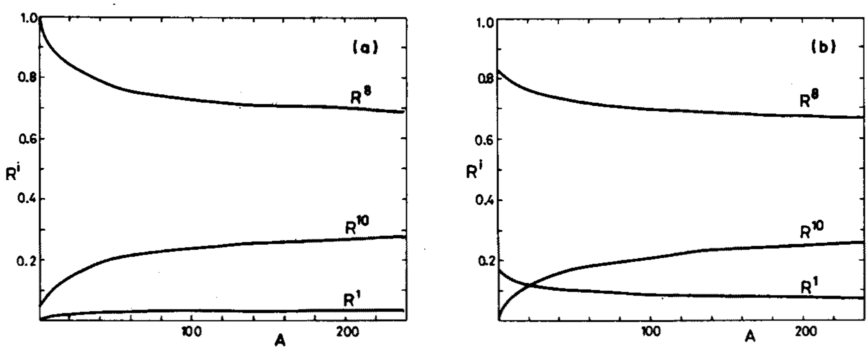

Fig. 2. The relative contributions of the different colour configurations to the inelastic cross section $p^{\pm}A$ in (a) Model IIa and (b) Model IIb.

The numerical results depend on the assumed values of σ^8_{qN} and σ^1_{qN}. Assuming that the nucleon-nucleon cross section is saturated by the octet exchange, $\sigma^1_{qN} = 0$, (Model IIa) one obtains the A-dependence illustrated in Fig. 2a. In the single collision only the octet configuration can be produced. The contribution of the octet to the total cross section decreases with A. The singlet and the decuplet can occur only in the multiple scattering processes and these two components increase with A. The A-dependence of the colour configurations is different if one assumes that in the constituent-nucleon interaction the exchange of colour singlet is also present (IIb). In this case the singlet configuration can be produced also in a single constituent-nucleon collision. Fig. 2b shows the results which have been obtained assuming that the colour singlet exchange contributes 5 mb out of total 30 mb to the nucleon-nucleon inelastic cross section. In this case, like in the model with the statistical weights, the singlet and the octet components decrease with A. In all the versions of the model the singlet contribution is small. Nevertheless it can play the dominant role at very high x_F. Let us also note that in the Models I and IIb the singlet component decreases with A faster than the octet one.

4. Comparison with the experimental data

The most suitable data for analysis of discussed models come from the ACCMOR experiment (8) which provides us with the simultaneous measurements of the leading proton and antiproton spectra in x_F range 0.1-0.6 at the beam energy 120 GeV. In the Tables I and II the leading proton and antiproton spectra

$$f^{\pm}(x_F) = \frac{1}{\sigma_{\text{inel}}} \frac{d\sigma}{dx_F}(p^{\pm} + A \to p^{\pm}_{\text{leading}} + X) \tag{11}$$

are given. They have been extracted from the ACCMOR data for Be, Cu, Ag, W and U nuclear targets. Complementary data at higher x_F can be obtained from the FNAL experiment of Barton *et al.* [9] with 100 GeV proton beam.

TABLE I

The inclusive distributions $f^{+}(x_F)$ of the leading protons in inelastic proton-nucleus collisions

x_F	Be	Cu	Ag	W	U
0.15	.72±.05	.89±.05	.96±.06	.95±.06	1.00±.06
0.20	.74±.05	.73±.05	.79±.05	.80±.05	.81±.06
0.25	.67±.05	.73±.04	.67±.04	.67±.05	.72±.05
0.30	.63±.04	.66±.03	.61±.03	.65±.04	.57±.04
0.35	-	.61±.02	.62±.02	.58±.03	.59±.03
0.40	.58±.03	.57±.02	.52±.02	.52±.02	.53±.02
0.45	.59±.03	.50±.02	.47±.02	.43±.02	.46±.02
0.50	.55±.03	.43±.02	.40±.02	.39±.02	.39±.02
0.55	.51±.03	.41±.02	.41±.02	.37±.02	.37±.02
0.60	-	.40± .04	.33±.04	.31±.05	.32±.05

In the x_F range covered by the ACCMOR experiment we do not expect any significant contribution from the singlet fragmentation and Eq. (3) can be reduced to:

$$\frac{d\sigma}{dx_F}(p(\bar{p}) + A \to p(\bar{p}) + X) = \sigma^8(A) F^8_{p(\bar{p})}(x_F) + \sigma^{10}(A) F^{10}_{p(\bar{p})}(x_F) \,. \tag{12}$$

TABLE II

The inclusive distributions $f^{-}(x_F)$ of the leading antiprotons in inelastic antiproton-nucleus collisions

x_F	Be	Cu	Ag	W	U
0.15	.59±.06	.62±.04	.65±.04	.62±.05	.58±.06
0.20	.58±.06	.61±.04	.62±.04	.61±.04	.57±.05
0.25	.62±.06	.56±.03	.55±.03	.53±.04	.54±.05
0.30	.57±.05	.51±.03	.53±.03	.42±.04	.47±.04
0.40	.51±.04	.46±.03	.42±.03	.39±.03	.46±.03
0.45	.52±.04	.40±.03	.40±.03	.37±.03	.40±.03
0.50	.51±.04	.42±.03	.33±.03	.33±.03	.37±.03
0.55	.41±.04	.32±.03	.34±.03	.30±.03	.35±.03
0.60	-	.32±.04	.22±.04	.29±.04	.23±.04

We determine $F^i(x_F)$ at each value of x_F from the minimum χ^2 fit to the data on the five targets (Be, Cu, Ag, W, U) separately for the spectra of leading protons and antiprotons. The resulting fragmentation functions are shown in Figs 3 and 4 for the Models I and IIa. In the x_F region below 0.4 the results are consistent with the expectations discussed in Section 2.

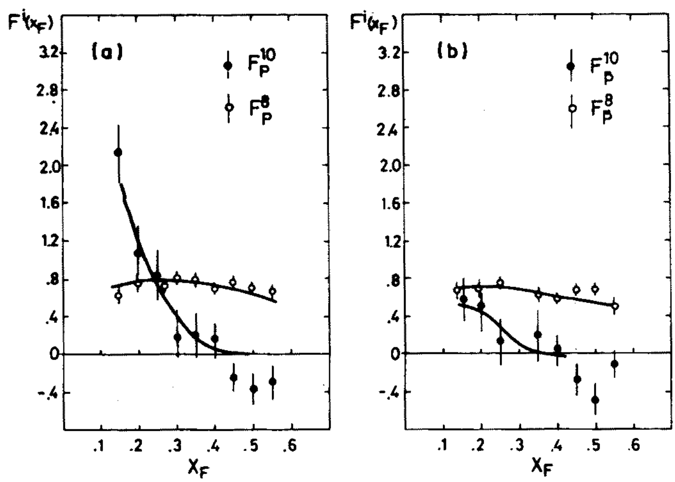

Fig. 3. Fragmentation functions in the Model I fitted to the inclusive leading proton and antiproton spectra: (a) proton-nucleus $f^{+}(x_F)$ and (b) antiproton-nucleus $f^{-}(x_F)$.

The decuplet fragmentation function is appreciable only below $x_F = 0.3$. For the proton data it shows fast decrease with increasing x_F. It is also strongly suppressed for the antiproton data. The octet fragmentation function is approximately flat and similar for p and $\bar{p}$ data. Comparison with the leading proton and antiproton spectra on hydrogen is presented in Fig. 5.

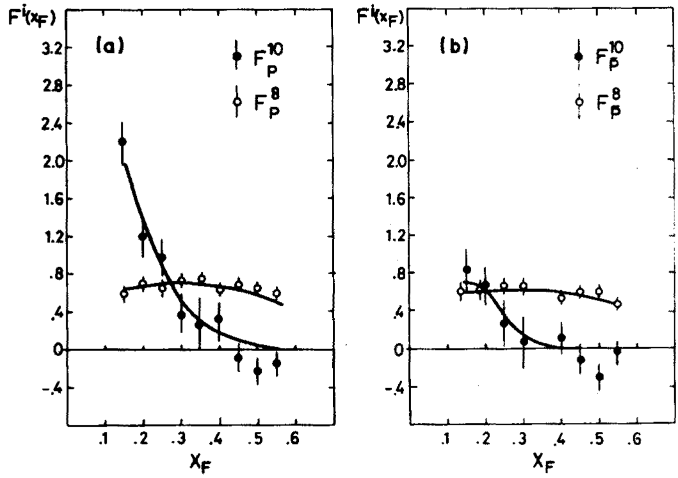

Fig. 4. Fragmentation functions in the Model IIa fitted to the inclusive leading proton and antiproton spectra: (a) proton-nucleus $f^+(x_F)$ and (b) antiproton-nucleus $f^-(x_F)$.

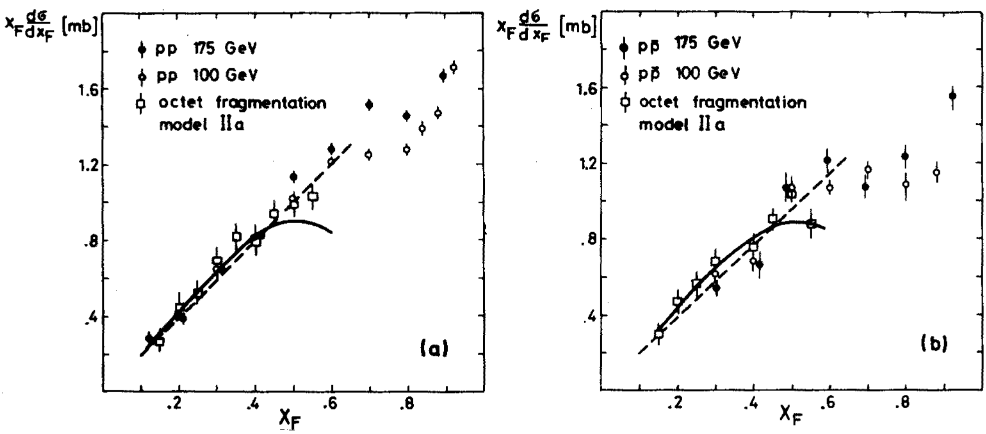

Fig. 5. Comparison of the octet fragmentation function with the inclusive cross sections: a) $x\frac{d\sigma}{dx}(pp \to p{+}X)$ and b) $x\frac{d\sigma}{dx}(\bar{p} \to \bar{p}{+}X)$. Solid and dashed lines represent the predictions of the Model IIa and the additive quark model respectively.

A fairly good agreement is found for x_F up to 0.5. Quality of the fits is shown in Figs 6 and 7. The model predictions were calculated from the fragmentation functions obtained by smoothing the values fitted at discrete x_F. Then the overall fit in the whole x_F range was performed. Up to $x_F \leq 0.4$ the data are described well by the models I and IIa with the octet component consistent with the hydrogen data. At the higher values of x_F this consistency breaks down and the octet fragmentation function be-

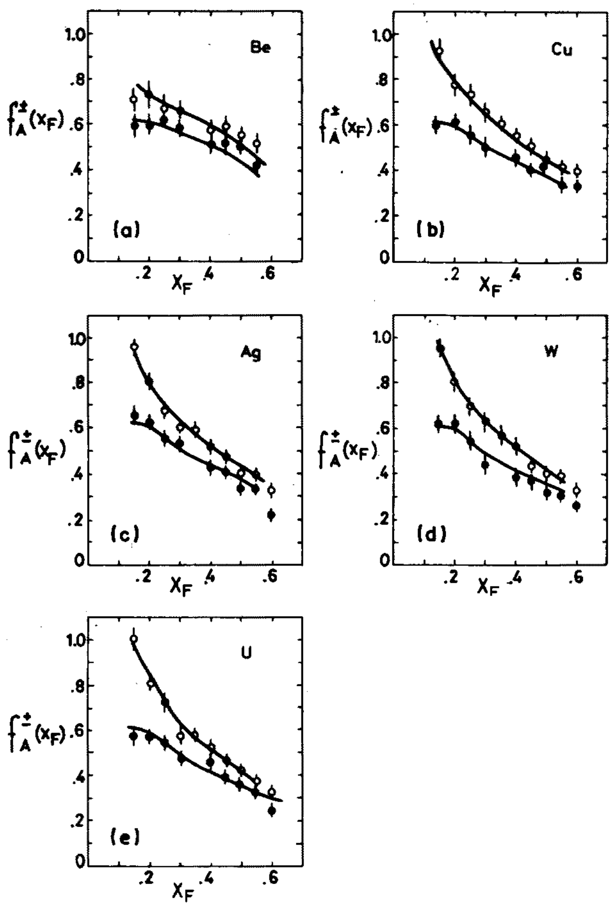

Fig. 6. Comparison of the ACCMOR data on the inclusive leading proton (∘) and antiproton (•) spectra $f^{\pm}(x_F)$ for Be, Cu, Ag, W, U targets with the predictions of the Model I (solid lines). The curves have been calculated from the fragmentation functions represented by the solid lines in Fig. 3.

comes smaller than the cross sections measured on the hydrogen (solid line in Fig. 5). Also the points obtained for the decuplet fragmentation functions take in this region negative values (see Figs 3 and 4). This means that the data demand a contribution which decreases with A faster than the octet component. In the models I and IIb such a contribution could come from the singlet fragmentation. This would imply, however, the singlet fragmentation function extending up to unexpectedly low values of x_F ($x_F \sim 0.5$). The problem is even more pronounced for the proton data of Barton *et al.* [9] at the highest measured x_F values. In Fig. 8 the A-dependence of the inclusive cross sections at $x_F \geq 0.8$ is shown together with the predictions

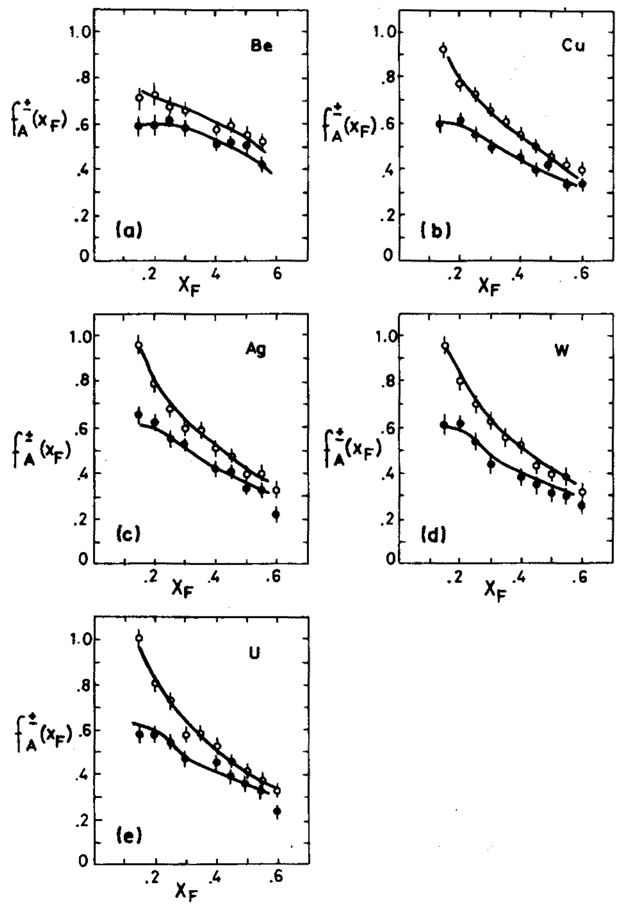

Fig. 7. Comparison of the ACCMOR data on the inclusive leading proton (o) and antiproton (•) spectra $f^{\pm}(x_F)$ for Be, Cu, Ag, W, U targets with the predictions of the Model IIa The curves have been calculated from the fragmentation functions represented by the solid lines in Fig. 4.

of several models. The A-dependence of the constituent quark models with colour at very high x_F is represented by the singlet (I,IIb) or the octet(IIa) components. These contributions are shown which give the strongest decrease with A for the models. Thus they set the lower limits within the corresponding models on the nuclear depletion ratio R at very high x_F. For the additive quark model the probability of wounding one quark is shown. For multiple collisions models the curve represents the probability of single collision. The data points and the theoretical curves are normalized to one at A=1. Among the constituent quark models with colour only the models with a significant contribution of the singlet exchange ($\geq$ 5mb) can

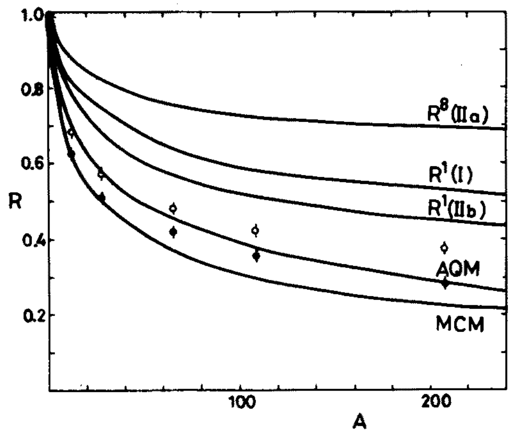

Fig. 8. The A-dependence of the proton inclusive cross sections at $x_F = 0.8$ (o) and $x_F = 0.88$ (•) [9] and the predictions of the models:
MCM — probability of the single collision in multiple collisions models;
AQM — probability of wounding one quark in the additive quark model;
R^8(IIa) — probability of producing the octet configuration in the Model IIa;
R^1(I) — probability of producing the singlet configuration in the Model I;
R^1(IIb) — probability of producing the singlet configuration in the Model IIb

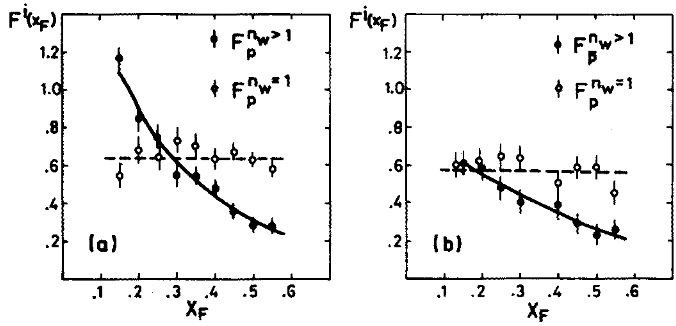

Fig. 9. Fragmentation functions in the additive quark model fitted to the inclusive leading proton and antiproton spectra: (a) proton-nucleus $f^+(x_F)$ and (b) antiproton-nucleus $f^-(x_F)$. $F^{n_w=1}(x_F)$ denotes the fragmentation function of the nucleon with one quark wounded and $F^{n_w>1}(x_F)$ - the fragmentation function of the nucleon with more than one quark wounded.

reproduce the nuclear depletion of the leading particles at $x_F \approx 0.8$. On the other hand, an attempt to describe the leading proton spectra through the dominant contribution of the singlet fragmentation in a wide x_F range requires rather high values of the integral $\int F^1(x_F)dx_F$ because the relative probability of the singlet configuration is rather low. Combining the FNAL-SAS [9] and the ACCMOR [8] data one obtains typically $1 \div 1.5$

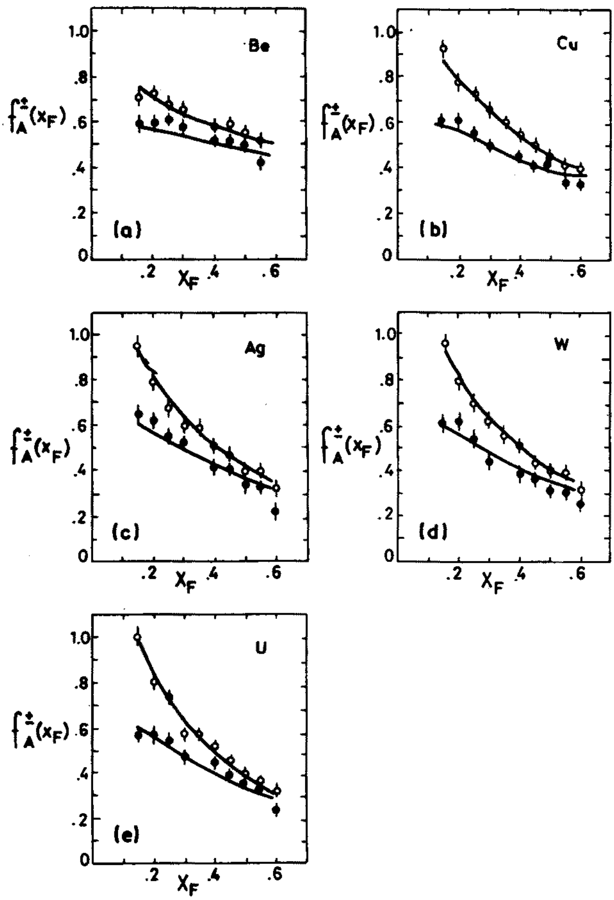

Fig. 10. Comparison of ACCMOR data on the inclusive proton (○) and antiproton (•) spectra $f^{\pm}(x_F)$ for Be, Cu, Ag, W, U targets with the predictions of the additive quark model (solid lines). The curves have been calculated from the fragmentation functions represented by the solid lines in Fig. 9.

for the integration range $0.45 < x_F < 0.88$. Such high values are clearly unacceptable. Neglecting the production of proton-antiproton pairs, which is known to be small, one expects for any of the fragmentation functions the integral smaller than one because fragmentations into neutrons or antineutrons are also possible. A further increase of the singlet exchange in the interaction mechanism can improve the agreement of the model with the data at $x_F \geq 0.8$. At the same time, however, the A-dependence of the octet component becomes too weak to describe the ACCMOR data at $x_F \leq 0.4$. Thus a large probability of the singlet exchange would require appreciable singlet fragmentation in the low x_F region.

5. Discussion of the results

The common feature of all the models presented in the previous section is that the A-dependence of the spectra originates from two groups of contributions, some of them increasing and some decreasing with A. Such an approach is not new. It has been noticed in several papers (see for example [10, 11] that the hadron-nucleus interactions can be described by the hydrogen-like component whose contribution decreases with A and the second one, specific to nuclear collisions, whose contribution increases with A. The models presented in this paper give a natural interpretation of these two components.

The failure of the models which assume that the particle production is determined exclusively by the total colour of the forward moving constituents is due to the weak A-dependence of the octet configuration. This configuration gives the dominant contribution decreasing with A in the Models I and IIb and the only one in the Model IIa. The assumption that the fragmentation into final hadrons depends only on the colour charge of the intermediate state implies that even after several collisions (or wounding more than one quark) the probability of producing the system identical to that produced in interactions with hydrogen remains high.

The ACCMOR data can be described well in the full x_F range by two components in the framework of the additive quark model [3–6]. This model also leads in a natural way to the two component picture. The hydrogen-like contribution comes from these collisions in which only one quark in the projectile is wounded. The second component corresponds to the interactions with more than one wounded quark. One can expect that the fragmentation functions describing fragmentations into baryons of the nucleons with two and three wounded quarks are fairly similar. In our analysis it has been assumed that these two components are the same. The results are shown in Figs. 9 and 10. It can be also seen from Fig. 8 that the A-dependence at $x_F \geq 0.8$ is well reproduced by the probability of wounding only one quark in the projectile.

In conclusion: the number of wounded quarks in the hadron leads to the better description of the data than the total colour charge. The assumption that the total colour charge of the produced system is the only parameter determining the subsequent fragmentation process leaves too much coherence in the projectile system after the multiple scattering in the nucleus. The above assumption is not the inherent feature of the constituent quark models with colour. However, without this assumption the predictive power of these models is significantly reduced.

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