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A constituent quark model with colour degrees of freedom confronts the data on hadron-nucleus interactions*

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Abstract

Three versions of a model with colour excitations of constituent quarks are examined using inclusive leading proton and antiproton spectra in nuclear interactions at high energies. The comparison with experimental data excludes the models in which fragmentation into leading final hadrons depends only on the colour charge of constituents in an intermediate system.

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1 Introduction

The question is still open, if in scattering on nuclei one can observe new effects, not appearing in interactions on single nucleon. According to the wounded quark models [1-4] such effects may occur when at least two constituent quarks are wounded. An interesting example of a process in which such effects may be manifest is baryon number annihilation on nuclei. In Ref.[5] the colours of constituent quarks have been taken into account. In general particle production may depend on both the number of wounded constituents and the colour charges of constituents. In Ref.[5] a simle assumption was proposed that production of fast particles depends only on total colour charge of a fragmenting system of constituents. In the present paper we examine three versions of the wounded quark model with colour. We use the existing data on inclusive leading proton and antiproton spectra in the reactions:

$$pA \rightarrow p + anything \quad (1)$$

$$\bar{p}A \rightarrow \bar{p} + anything \quad (2)$$

of ACCMOR [6] (reactions 1 and 2, $E_{beam} = 120GeV$) and FNAL-SAS [7] (reaction 1, $E_{beam} = 100GeV$) experiments.

The paper is organised as follows. In the next section we present general assumptions and predictions of the wounded quark model taking into account colour degrees of freedom. In sect. 3 three specific versions of the model are discussed. Comparison with experimental data is performed in sect. 4. Results are discussed in sect. 5.

2 Additive quark model with colour degrees of freedom

The general assumption of wounded quark models is that particle production in the projectile fragmentation region depends on number of wounded constituents of the projectile. According to an extension of this model proposed in Ref. [5] in order to take into account colour degrees of freedom, the constituent quarks before and after a collision transform as colour triplets and constituent antiquarks as the complex conjugate representations.

In case of baryon interactions three valence quarks after a collision can carry a colour charge belonging to a representation of the reduction $3\otimes3\otimes3 = 1\oplus8\oplus8\oplus10$. Overall colour conservation allows for singlet-singlet and octet-octet configurations in baryon-baryon scattering. Additionaly decuplet-antidecuplet is possible in baryon-antibaryon collisions, this requires however wounding of at least two quarks and antiquarks in baryon and antibaryon. The configuration $10 - 10^*$ is also allowed in baryon-nucleus and antibaryon-nucleus interactions.

These intermediate colour configurations are neutralised in a process of fragmentation into hadrons. Assumption of the model is that the functions describing fragmentation of a projectile depend only on colour charge of the intermediate system. Thus, the proton interactions with nuclear targets are described by three fragmentation functions in the projectile fragmentation region:

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

where $F^i(x)$ denotes a fragmentation function of colour state i and σ^i_{pA} are cross-sections for production of the corresponding colour configurations.

Contributions of different colour states to the total cross-section depend on further assumptions about production mechanism, which will be presented in the next section. Before doing that, let us discuss qualitatively some expected features of fragmentation functions in baryon and antibaryon interactions. The octet configuration corresponds to the pomeron exchange and it will be a dominating contribution in an interaction with a single nucleon in the region where diffractive disociacion can be neglected. The singlet configuration corresponds to diffractive excitation of scattered particles and it is expected that it will fragment into fast baryons (antibaryons). It is more difficult to reconstruct a baryon and antibaryon from decuplet and antidecuplet states, which are completly symetric in colour. If they neutralise their colour by creation of three $q\bar{q}$ pairs it would lead to a fragmentation into fast mesons and to effective transfer of the baryon number to the target fragmentation region. This gives a new mechanism of baryon number annihilation, as antibaryons in this region annihilate with a high probability. Thus we expect in baryon-nuclens scattering a soft component in baryon spectra, which should be strongly supressed in antibaryon interactions.

3 Cross-sections for production of intermediate colour states

Cross-section for production of a state of a given colour depends on the interaction mechanism. We shell consider two extreme cases.

In the first model (I) we assume that after an interaction constituent quarks loose their coherence and probabilities of different colour configurations are given by statistical wights. Thus, if only one quark is wounded, the singlet or octet of colour are produced with relative probabilities 1/9 and 8/9 respectively. In case of more then one quark having been wounded, three colour configurations are possible with probabilities 1/27 for singlet, 16/27 for octet and 10/27 for decuplet. The A-dependence of these contributions to the total cross-section is determined by a probability of wounding one quark in the projectile. In this version of the model there are two components in the total cross-section, which decrease with A: singlet and octet, and one, coming from decuplet configuration, which increases with A. This is ilustrated in Fig. 1.

The second version of the model (II), which was discussed in [5] assumes complete coherence of constituent quarks after an interaction. Single constituents can effectively emit or absorb only an octet or singlet of colour, and probabilities of producing different intermediate colour states depend on number of absorption of colour octets by constituent quarks. In [5] a formula for the cross-section of the decuplet intermediate state was derived.

Analogously one can obtain expressions for remaining two colour configurations. Here we list furmulae for all intermediate states:

$$\sigma^1_{BA} = \frac{1}{27}\int d^2b[1 + 20(1 - \frac{27}{8}\hat{\sigma}^8_{qN})^A + 6(1 - \frac{9}{4}\hat{\sigma}^8_{qN})^A \tag{4}$$
$$-27(1 - 3(\hat{\sigma}^8_{qN} + \hat{\sigma}^1_{qN}]$$
$$\sigma^8_{BA} = \frac{8}{27}\int d^2b[2 - 5(1 - \frac{27}{8}\hat{\sigma}^8_{qN})^A + 3(1 - \frac{9}{4}\hat{\sigma}^8_{qN})^A] \tag{5}$$
$$\sigma^{10}_{BA} = \frac{10}{27}\int d^2b[1 + 2(1 - \frac{27}{8}\hat{\sigma}^8_{qN})^A - 3(1 - \frac{9}{4}\hat{\sigma}^8_{qN})^A] \tag{6}$$

where

$$\hat{\sigma}^i_{qN} = \sigma^i_{qN}\int dz\rho_A(b,z) = \sigma^i_{qN}T(b), ...(i = 1, 8) \tag{7}$$
$$\sigma_{inel} = \int d^2b[1 - (1 - 3(\hat{\sigma}^8_{qN} + \hat{\sigma}^1_{qN}))^A] \tag{8}$$

The numerical results depend on the assumed values of σ^8_{qN} and σ^1_{qN}, the cross-sections for quark interaction via octet and singlet exchange. Assumption, that the total inelastic cross section is described by octet exchange, i. e. $\sigma^1_{qN} = 0, \sigma^8_{qN} = \frac{\sigma_{NN}}{3}$ (model version IIa), leads to A-dependence illustrated in fig. 2a. For a single collision only a colour octet can be produced, and its contribution to the total cross-section decreases with A. Singlet and decuplet configurations can occure only in a multiple scattering and these two componenets increase with A.

The situation is different if one assumes, that in an interaction also exchange of colour singlet is present (IIb). In this case a singlet configuration can be also produced in a single collision. Fig. 2b shows results with the assumption that 5 mb out of 30 mb total inelastic nucleon-nucleon cross-section comes from colour singlet exchange. In this case, like in the model with statistical weights, two components, singlet and octet decrease with A. In all versions of the model the singlet contribution is very small, but it can play a dominant role at wery high x_F. Let us aslo note that in the models I and IIb the singlet component decreases with A faster than the octet one.

4 Comparison with experimental data

The most suitable data for analysis of discussed models come from ACCMOR experiment [6], which provides us with simultaneous measurements of leading proton and antiproton spectra in x_F range 0.1-0.6 at beam energy 120 GeV. Complementary data at higher x_F can be obtained from FNAL (Barton et al. [7]) with 100 GeV proton beam.

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

$$\frac{d\sigma}{dx_F}(p(\bar{p}) + A \to p(\bar{p}) + X) = \sigma^8(A)F^8_{p(\bar{p})}(x_F) + \sigma^{10}(A)F^{10}_{p(\bar{p})}(x_F) \tag{9}$$

In order to avoid parametrising unknown functions we determine $F^i(x_F)$ at each value of x_F by a minimum χ^2 fit to five targets (Be, Cu, Ag, W, U), seperately for leading proton and antiproton spectra. Resulting fragmentation functions are shown in figs. (3-4) for models I and IIa. In the x_F region below 0.4 both versions of the model give results in general consistent with expectations discussed in sect. 2. Decuplet fragmentation function is significant only below $x_F = 0.3$, for proton data it shows fast decrease with increasing x_F and is strongly suppressed in antiproton data. Fragmentation functions of octet are approximately flat and similar for p and $\bar{p}$ data. Comparison with leading proton and antiproton spectra on hydrogen is presented in fig. 5, and shows a good agreement for x_F up to 0.5. Quality of the fits is shown in figs. 6-7, where the lines were calculated from fragtmentation functions obtained by smoothing the points found at discrete x_F values and performing an overall fit in the whole x_F range. Up to $x_F \leq 0.4$ the data are well described by the both versions of the model, with the octet component consistent with hydrogen data. At higher x_F values this consistency breaks down, which is manifested by fast decrease of octet fragmentation function, below cross-sections measured on hydrogen (solid line in fig. 5). Also the points obtained for decuplet fragmentation functions take in this region systematicaly negative values (see figs. 3-4). It means that the data demand a contribution which decreases with A faster than the octet component. In the versions I and IIb such a contribution could come from singlet fragmentaation, which should however extend to unexpectedly low x_F values. The problem is even more pronounced for proton data of Barton et alo. [7], at the highest measured x_F values. In fig. 8 the A-dependence of inclusive cross-sections at $x_F \geq 0.8$ is shown together with predictions of several models. The A-dependence of wounded quark models with colour at very high x_F is represented by singlet (I,IIb) or octet(IIa) components. (For all versions of the model we show the contribution which gives the strongest decrease with A. This components set the model limits on nuclear depletion at very high x_F). For additive quark model [1-4] probability of wounding one quark is shown, for multiple collisions models the curve represents a probability of single collision. The data points and the theoretical curves are normalized to unity at A=1. Among wounded quark models with colour which have been discussed, only the model with significant contribution of singlet exchange ($\geq$ 5mb) can reproduce the nuclear depletion of leading particles at $x_F \approx 0.8$. On the other hand, as the relative probability of producing a singlet is rather low, describing the leading proton spectra with a main contribution of singlet fragmentation in a wide x_F range requires very high value of the integral $\int F^1(x_F)dx_F$. Combining FNAL-SAS [7] and ACCMOR [6] data leads to the inegral value of $1 \div 1.5$ for the integration range $0.45 < x_F < 0.88$. Further increase of singlet exchange in the interaction mechanism can improve a consistency of the model with the data at $x_F \geq 0.8$, but at the same time it causes a weaker A-decrease of the octet component as an intermediate state. The A-dependence of the octet component becomes to weak to describe ACCMOR data at $x_F \leq 0.4$ and consequently it would lead to extension of singlet fragmentation up to unreasonably low x_F region.

5 Discussion of results

The analysis presented in the previous section technicaly comes to description of the data by a sum of two functions: one of them gives a contribution increasing with atomic mass number of a target and the second one decreasing with A. Such approach is not new and it was noticed in several papers (see eg. refs. [8],[9]), that hadron-nucleus interactions can be described by a hydrogen-like component decreasing with A and the second one, specific to nuclear collisions. The models presented in this paper give a natural interpretation of these two components.

The failure of discussed models is due to the weak A-dependence of the octet configuration, the dominant component which gives contribution decreasing with A in the model versions I and IIb, and the only one in the model version IIa. Assumption that a fragmentation into final hadrons depends only on the colour charge of the intermediate state causes that even after several collisions (or after wounding more than one quark), probability of producing a system identitcal to that produced in interactions with hydrogen remains high.

On the other hand, the ACCMOR data can be described well in the full x_F range by two components in the framework of the Additive Quark Model ([1-4]), which gives also a natural interpretation of the two component picture. Hydrogen-like contribution comes from collisions in which a single quark was wounded. The second component corresponds to interactions with more wounded quarks. One can expect that fragmentation functions of nucleon with two or three quarks wounded into a baryon are very similar. In the analysis we assumed that these two components are the same. Results are shown in figs. 9-10. Also, as can be seen from fig. 8, the A-dependence at $x_F \geq 0.8$ is well reproduced by the probability of wounding a single quark.

In conclusion, the number of wounded quarks in a hadron is a better characteristics of hadron-nucleus inetractions then the colour charge. Taking into account only a colour charge of produced system, and with neglecting the number of collisions or number of wounded constituents leaves too much coherence in a projectile after multiple scattering in nucleos. The above assumption is not an inherent feature of the discussed model, releasing it however would lead to too big freedom of the model, reducing its predictive power.

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Figure captions

Fig. 1 The ratios of the cross-sections for different colour configurations to the total inelstic cross-section on a nucleus A in the model version I.

Fig. 2a The ratios of the cross-sections for different colour configurations to the total inelstic cross-section on a nucleus A in the model version IIa.

Fig. 2b The ratios of the cross-sections for different colour configurations to the total inelstic cross-section on a nucleus A in the model version IIb.

Fig. 3 Fragmentation functions in the model version I fitted to the inclusive proton and antiproton spectra:
a) $\frac{1}{\sigma_{inel}}(pA \to p_{leading} + anything)$ b) $\frac{1}{\sigma_{inel}}(\bar{p}A \to \bar{p}_{leading} + anything)$

Fig. 4 Fragmentation functions in the model version IIa fitted to the inclusive proton and antiproton spectra:
a) $\frac{1}{\sigma_{inel}}(pA \to p_{leading} + anything)$ b) $\frac{1}{\sigma_{inel}}(\bar{p}A \to \bar{p}_{leading} + anything)$

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

Fig. 6 Description of the inclusive prooton and antiproton spectra in the model version I for Be, Cu, Ag, W, U targets.
$f^{\pm}(x_F) = \frac{1}{\sigma_{inel}}\frac{d\sigma}{dx_F}(p(\bar{p} + A \to p(\bar{p}) + anything)$
The curves were calculated from the fragmentation functions represented by solid lines in fig. 3.

Fig. 7 Description of the inclusive prooton and antiproton spectra in the model version IIa for Be, Cu, Ag, W, U targets.
$f^{\pm}(x_F) = \frac{1}{\sigma_{inel}}\frac{d\sigma}{dx_F}(p(\bar{p} + A \to p(\bar{p}) + anything)$
The curves were calculated from the fragmentation functions represented by solid lines in fig. 4.

Fig. 8 Tha A-dependence of proton inclusive cross-sections at $x_F = 0.8$ (o) and $x_F = 0.88$ (o) [7] and predictions of hadron-nucleus interaction models:
MCM - probability of single collision in multiple collisions models
AQM - probability of wounding one quark in additive quark models
R^8(IIa) - probability of producing octet configuration in the model IIa
R^1(I) - probability of producing singlet configuration in the model I
R^1(IIb) - probability of producing singlet configuration in the model IIb

Fig. 9 Fragmentation functions in the additive quark model fitted to the inclusive proton and antiproton spectra:

a) $\frac{1}{\sigma_{inel}}(pA \rightarrow p_{leading} + anything)$ b) $\frac{1}{\sigma_{inel}}(\bar{p}A \rightarrow \bar{p}_{leading} + anything)$
$F^{n_w=1}(x_F)$ - fragmentation function of nucleon with one quark wounded
$F^{n_w>1}(x_F)$ - fragmentation function of nucleon with more than one quark wounded

Fig. 10 Description of the inclusive prooton and antiproton spectra in the additive quark model with two fragmentation functions for Be, Cu, Ag, W, U targets.
$f^{\pm}(x_F) = \frac{1}{\sigma_{inel}} \frac{d\sigma}{dx_F}(p(\bar{p} + A \rightarrow p(\bar{p}) + anything)$
The curves were calculated from the fragmentation functions represented by solid lines in fig. 9.

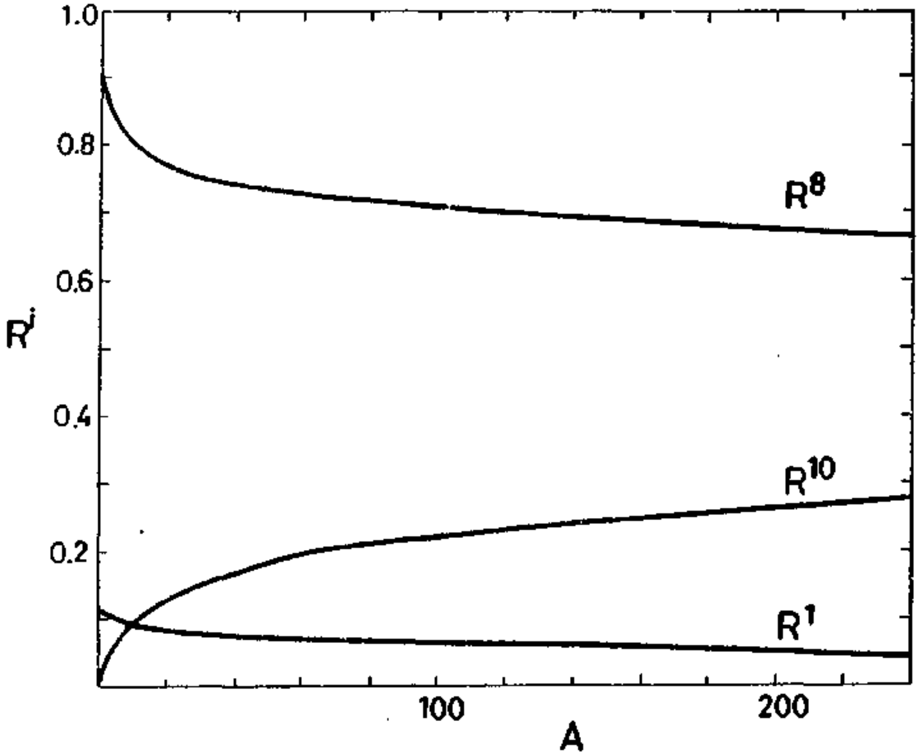
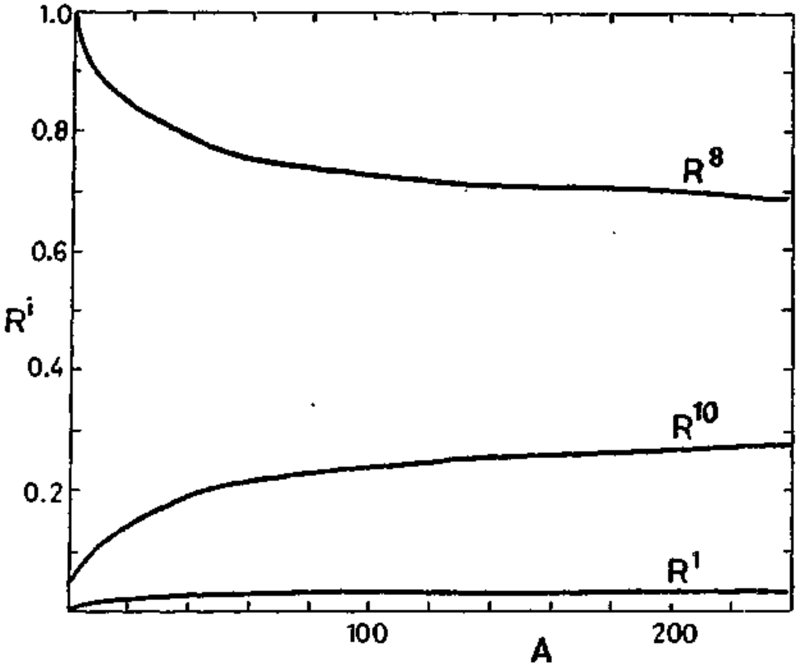


Fig . 1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R^i
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A

Fig. 2a

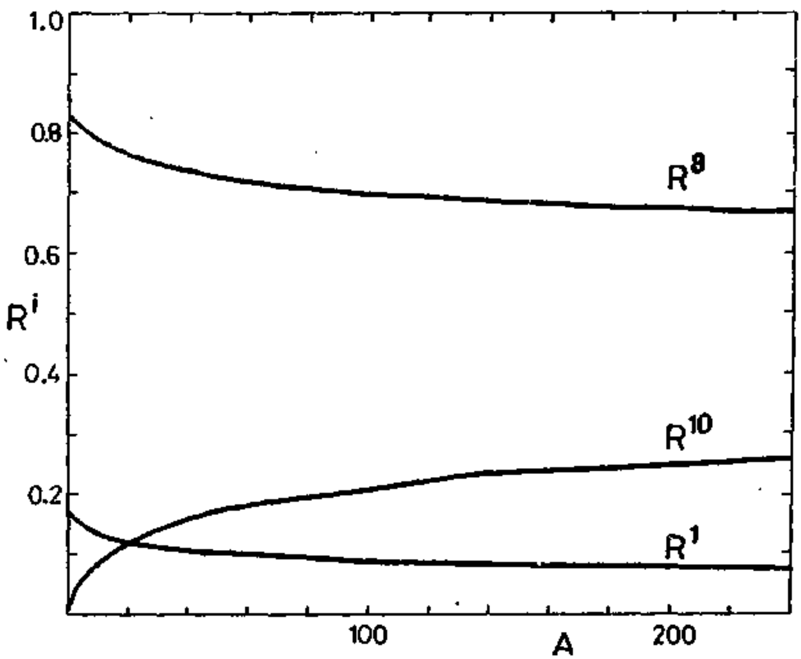
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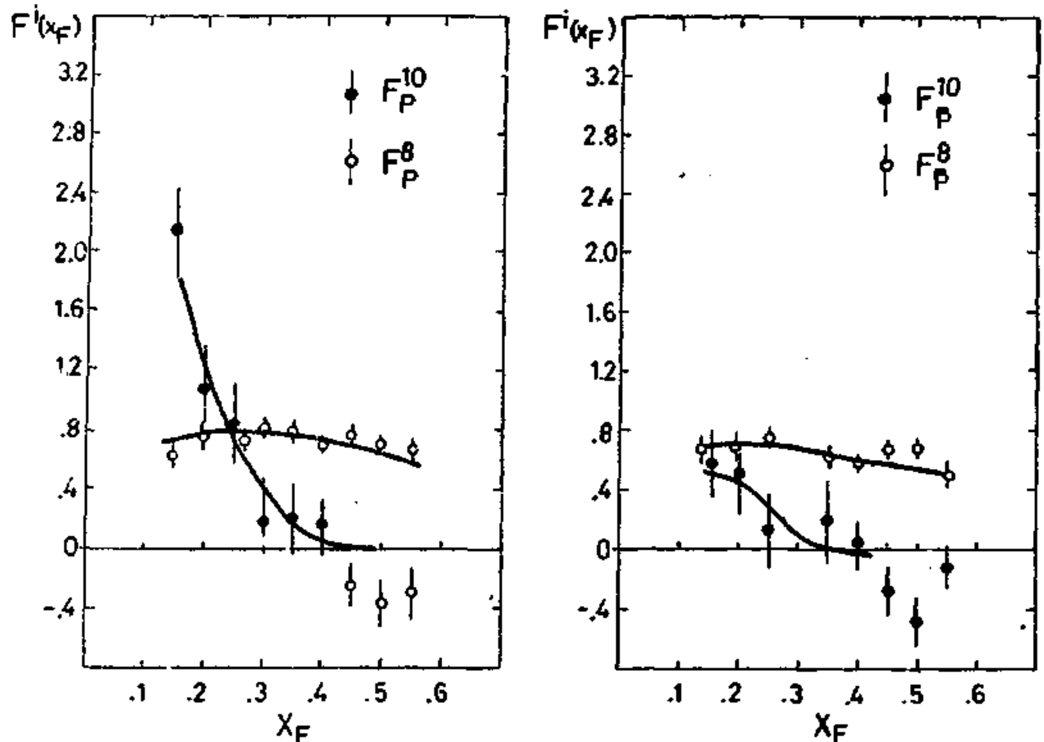
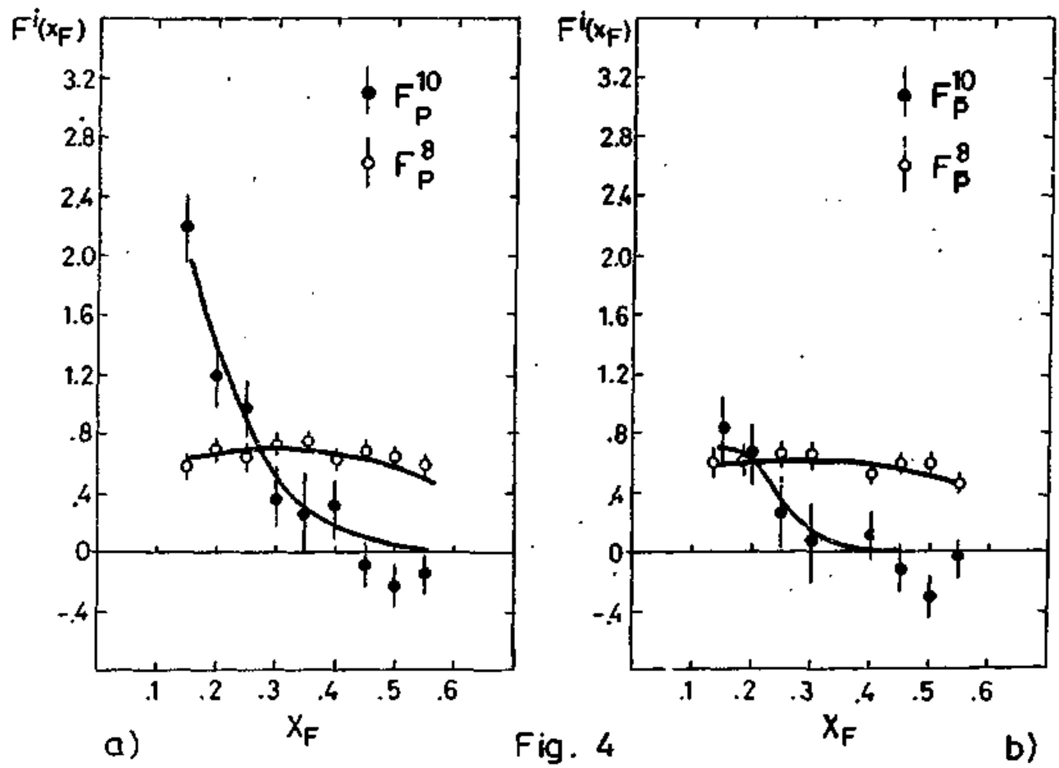
Fig. 2b



a) Fig. 3 b)



a) Fig. 4 b)

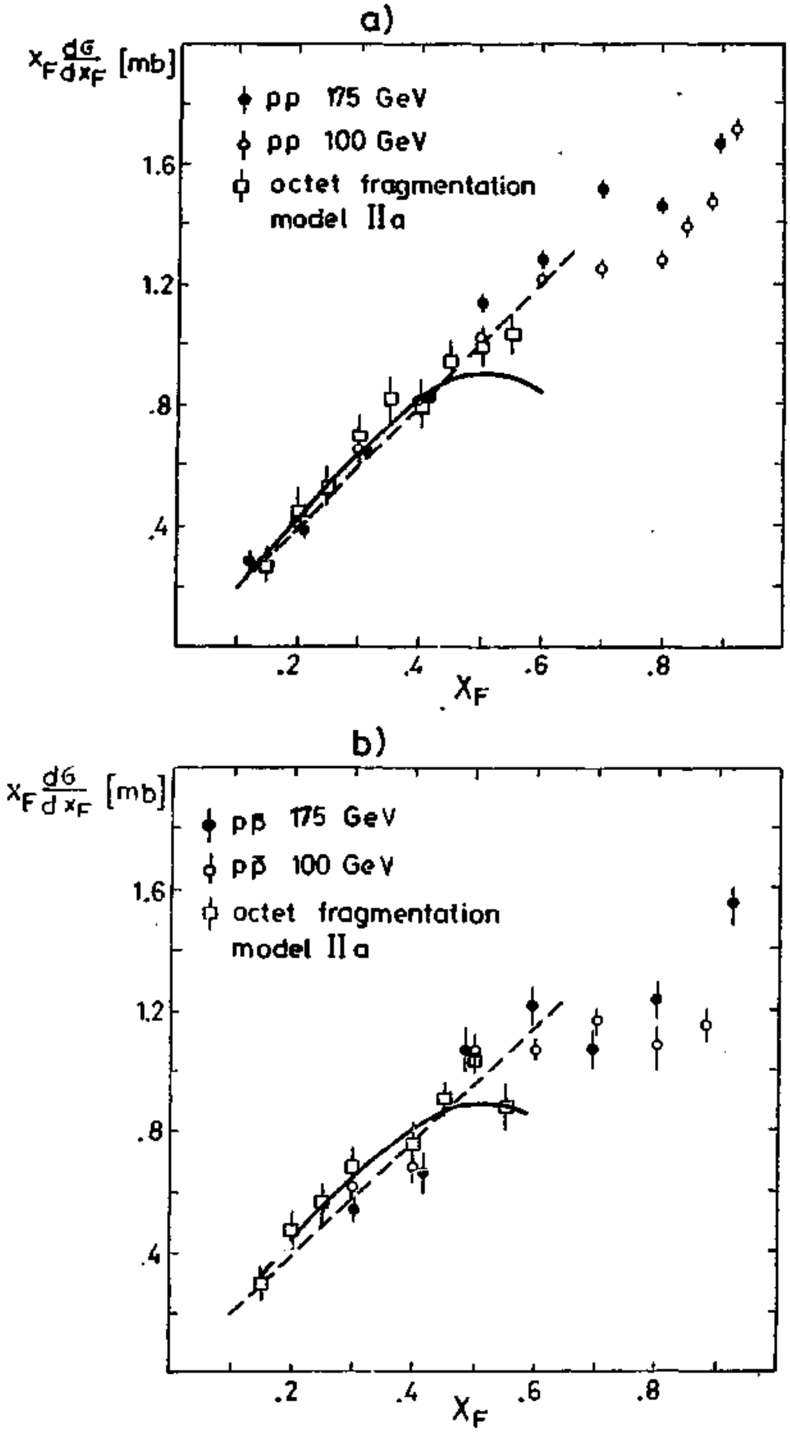

a)
$x_F \frac{d\sigma}{dx_F}$ [mb]
pp 175 GeV
pp 100 GeV
octet fragmentation model IIa
1.6
1.2
.8
.4
.2
.4
.6
.8
X_F
b)
$x_F \frac{d\sigma}{dx_F}$ [mb]
p$\bar{p}$ 175 GeV
p$\bar{p}$ 100 GeV
octet fragmentation model IIa
1.6
1.2
.8
.4
.2
.4
.6
.8
X_F

Fig. 5

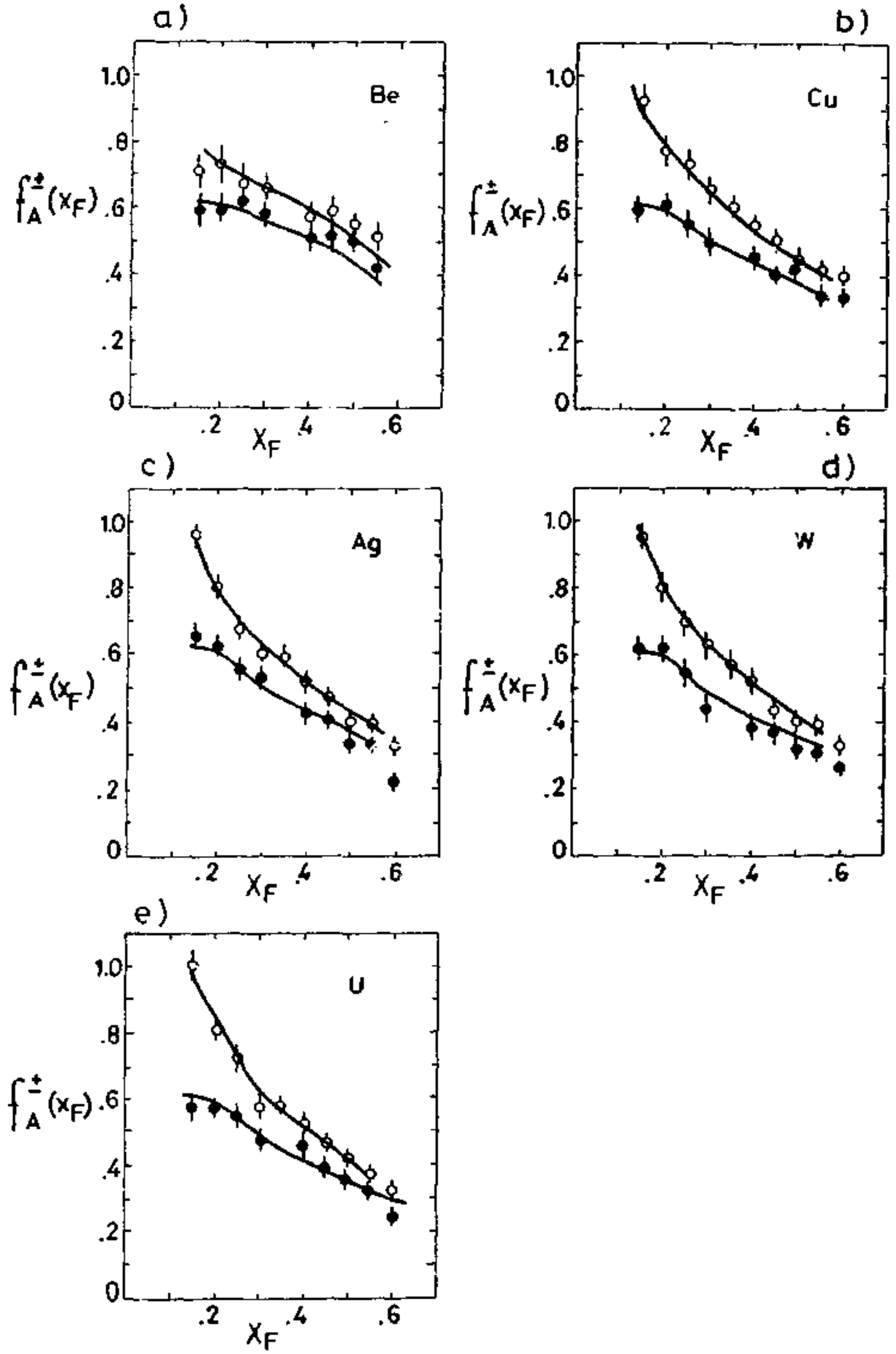


Fig. 6

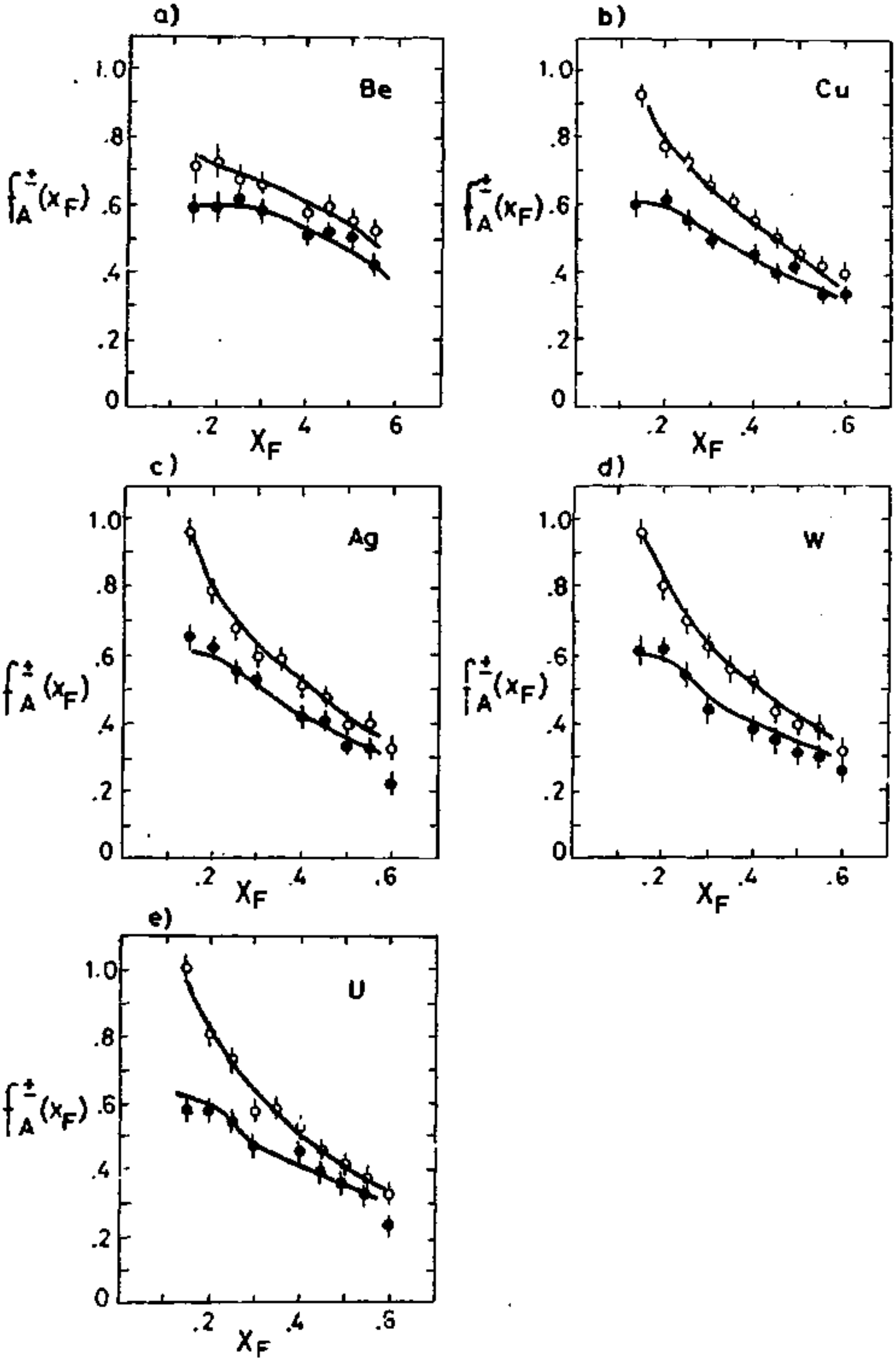


Fig . 7

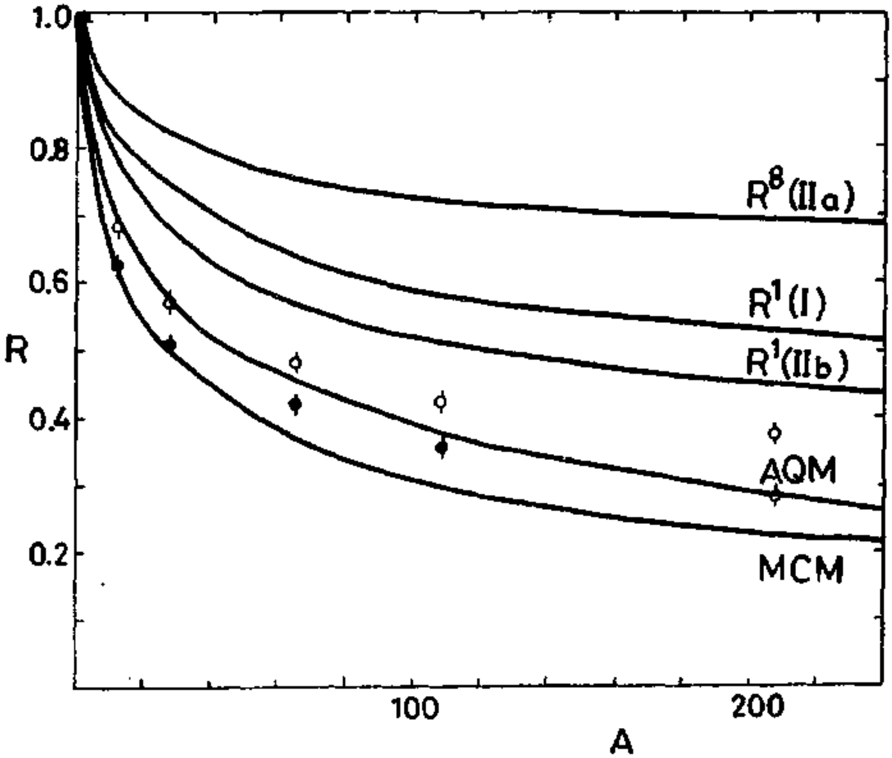


Fig. 8

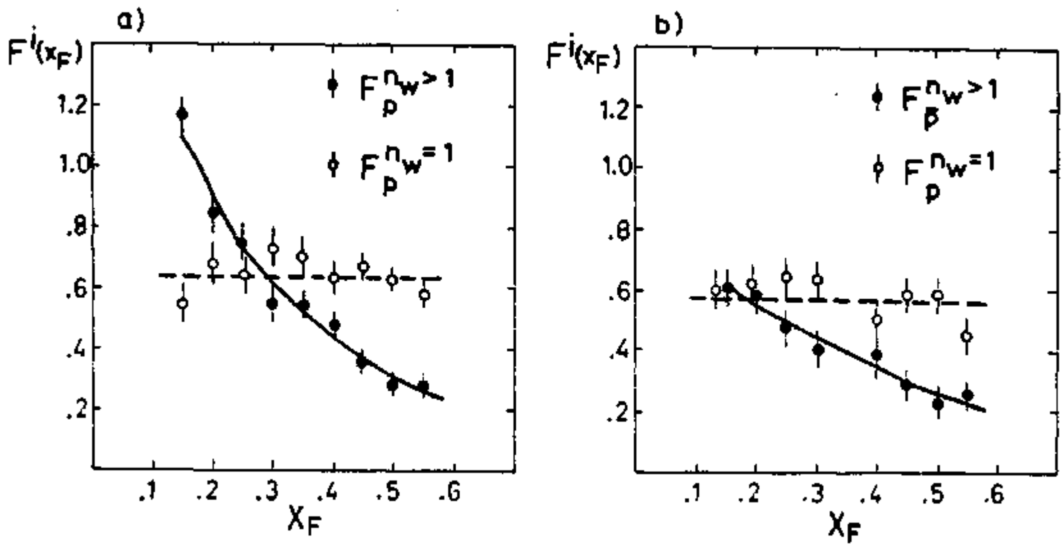


Fig . 9

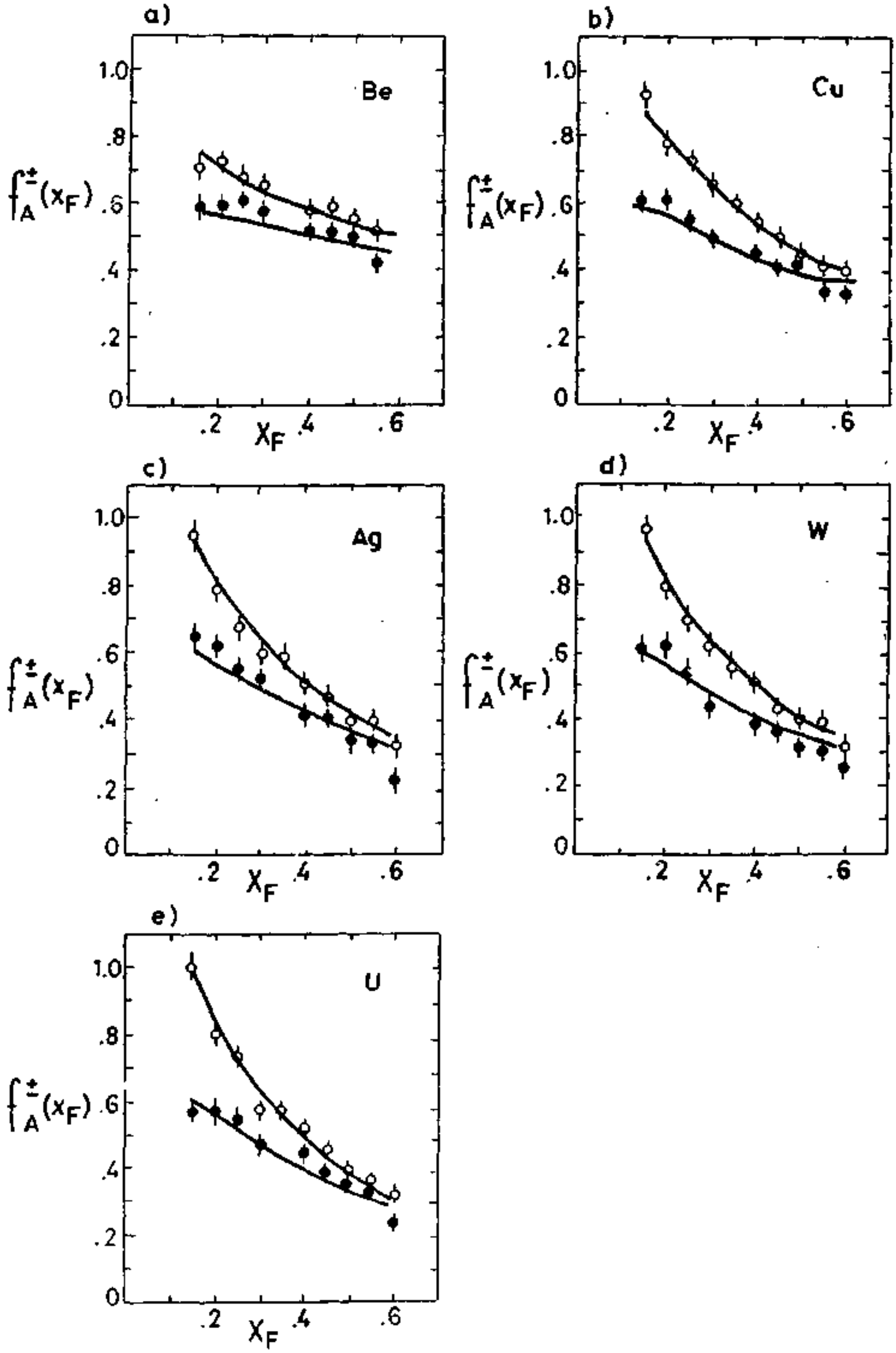


Fig . 10