FERMILAB-Pub-78/75-THY
September 1978

PARTICLE PRODUCTION FROM NUCLEAR TARGETS AND THE STRUCTURE OF HADRONS

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Summary. Production processes from nuclear targets allow to study interactions of elementary hadronic constituents in nuclear matter. The information thus obtained on the structure of hadrons and on the properties of hadronic constituents is presented. Both "soft" (low momentum transfer) and "hard" (high momentum transfer) processes are discussed.

Invited talk at the III Multiparticle Symposium, Tabor 2-7 July 1978.

1. Introduction

It is now generally recognized that interactions of high--energy hadrons with nuclear targets give a unique possibility of studying the hadronic interactions over very short time after the collision. The extensive discussion of this problem was given in several reports at previous multiparticle meetings [1-4] (where also earlier references can be found) so there is no necessity to repeat it here in detail. In this talk I shall thus concentrate on only one aspect: the information one can obtain on <u>hadronic</u> structure from high-energy <u>nuclear</u> experiments.

The main idea here is that, by studying the behaviour of hadrons just after the collision took place (which is possible by using nuclear targets) one learns about interaction of hadronic constituents (which were present in the incident hadron and "shaken off" during the collision) before they have time to change again into ordinary hadrons. Such a picture of hadronic interactions with nuclei does indeed get support from the data. There are other possibilities of explaining data [5] but I shall not discuss them here.

As is clear from the preceding remarks, in this approach the nucleus is treated as a part of apparatus, a kind of detector which helps to observe phenomena non-accessible to ordinary detectors used in high-energy physics. We are thus interested in details of nuclear structure only as far as they are necessary to understand our detector. In most applications is seems justified to treat nucleus as a collection of quasi-independent nucleons. This description shall be used here unless stated otherwise. It is true that this is not the only possibility [5],[6] and that there are indications for collective phenomena inside nuclei [7], but we shall not enter into these problems.

The subject splits naturally into two parts: low momentum transfer and high momentum transfer phenomena. In low p_t interactions one studies the collective interactions of groups of hadronic constituents travelling through the nuclear matter. One thus learns about possible forces and correlations between them. In high-transfer interactions usually one or two constituents are kicked off from the projectile and/or target. One has thus a chance to study their individual interactions in nuclear matter (hopefully before the confinement forces start to operate and change them into normal hadrons).

In the next section the low momentum transfer collisions are described. High transfer phenomena are discussed in Section 3.

2. Low p_t phenomena

2.1. Brief summary of the present status

(i) It is experimentally established that there is very little (if any) intra-nuclear cascading by the fast hadrons produced in the hadron-nucleus collisions. This conclusion follows from the experimental observation that the multiplicity of particles produced in collisions with heavy nuclei is only slightly higher than the one observed in hydrogen [8]. The ratio $R_A = n_A/n_H$ can be reasonably parametrized by the formula [9]

$$R_A = \frac{1}{2}(1+\bar{\nu}_h) \qquad (2.1)$$

where $\bar{\nu}_h$ is the average number of collisions of the incident hadron h inside the nucleus

$$\bar{\nu}_h = \frac{A\,\sigma_H}{\sigma_A} \qquad (2.2)$$

Here n_A and n_H are multiplicities in nucleus and in hydrogen; σ_A and σ_N are corresponding inelastic nondiffractive cross-sections of the incident hadron h. Finally, A is the nuclear atomic number.

Since $\bar{\nu}_h$ never exceeds 4 even for heavy nuclei (see Fig. 1 where $\bar{\nu}_h$ is plotted against A for different incident hadrons), we see from Eq. (2.1) that the multiplication parameter R_A is indeed a rather small number, and thus the cascading is excluded.

(ii) The absence of intra-nuclear cascading implies that production of hadrons is a rather lengthy process, i.e. that the system going through the nucleus is quite different from the one observed in final state. In other words, the observed fast hadrons are created mostly outside of the nucleus. This situation is illustrated in Figure 2: An intermediate state created in the first collision lives long enough to travel through the whole nucleus and to interact with other nucleons. This interaction does not create immediately fast hadrons but it can excite intermediate state and perhaps produce some slow hadrons at large angles [10] in the laboratory frame. After leaving the nucleus the intermediate state decays into observed hadrons.

(iii) The theoretical discussion has to confront two problems: (a) the origin of the long-time character of the production of high-energy hadrons and (b) the nature and properties of the intermediate state travelling through the nucleus. The first of these problems was discussed extensively in recent years in the context of many different theories and models [1-4,11]. A general conclusion reached in these investigations is that the long-time character of "hadronization" finds a natural explanation as being a general feature of field theory. Actually, its origin is even more fundamental and can be traced to the uncertainty principle [1, 10]. The time scales for production of hadrons suggested by such arguments can be estimated from the formula

$$t = \frac{1}{E - p_{\parallel}} = \frac{e^{y}}{\sqrt{p_\perp^2 + m^2}} . \qquad (2.3)$$

t is very long for the typical high-energy low transverse momentum secondaries. Thus the hadrons are created well outside the nucleus and consequently do not cascade.

As to the specific nature of the intermediate state, the problem is still open and this is in fact a "hot" issue at the moment. It will be discussed in more detail later in this Section.

2.2. More about the data

A typical example of the A-dependence of the single-particle spectrum is presented in Fig. 3. The exponent α plotted in the Figure 3 describes the A-dependence of the spectrum according to the formula

$$d\sigma_A = A^{\alpha} d\sigma_H \qquad (2.4)$$

In this plot, the value $\alpha = \alpha_0 = 0.69$ corresponds to particle multiplicity independent of the nuclear size $\frac{1}{\sigma_A} \frac{E d\sigma_A}{d^3 p} = \frac{1}{\sigma_H} \frac{E d\sigma_H}{d^3 p}$. The value $\alpha = 1.0$ gives the multiplicity proportional to average number of collisions of the incident particle $\bar{\nu}_h$, given by Eq. (2.2).

One sees three characteristic features of the data:

(a) In the central rapidity region, $3 \lesssim y_{lab} \lesssim 5$, α is approximately independent of y_{lab} and $\alpha > \alpha_0$.

(b) In the forward region, close to maximal rapidity α falls below α_0 . Thus, in this region the number of particles decreases with increasing nuclear number. The transition point $(\alpha = \alpha_0)$ occurs at approximately two units of rapidity below the maximal one.

(c) The value of α is everywhere significantly smaller than 1.

These general features of the data are observed in all high energy experiments. For recent reviews, see Ref. [9], [13] and [14].

At rapidities below $y_{lab} = 2$ (target fragmentation region - not shown in Figure 3) the experimental situation is slightly less clear because of possible contamination by protons knocked-out from the target nucleus [15]. It seems, however, that the data in this region [16,19] are consistent with $\alpha \gtrsim 1$, thus indicating particle multiplicity proportional to the average number of collisions $\bar{\nu}_A$ and perhaps same amount of intra-nuclear cascading.

It is also interesting to see the variation of α with transverse momentum of the produced particles [18]. This is shown in Fig. 4, again taken from Ref. [12]. One observes increase of α for very small p_t below 200 MeV, particularly in the central region of rapidity. At high value of p_t we observe again increase of α which continues further on [19], as will be discussed in Section 3.

2.3. Qualitative interpretation of the data

The absence of intra-nuclear cascading leads naturally to the picture of hadron-nucleus collisions where the main factor which determines the A-dependence is the interaction of the incident particle (or its excited states) with the nucleons of the target. Such a picture implies several restrictions which are in good qualitative agreement with the data:

(a) For the secondaries produces in the central region of rapidity one expects $\alpha_0 \lesssim \alpha \leq 1$. Indeed, since the number of collisions $\bar{\nu}_A > 1$, the number of produced particles is expected not to be smaller than in hydrogen where the number of collisions is (by definition) equal 1. Thus $\alpha \gtrsim \alpha_0$. On the other hand, multiplication factor is expected not to exceed $\bar{\nu}_A$ (absence of cascading!) and thus

$\alpha \lesssim 1$.

(b) The leading particle spectrum should be shifted to lower rapidities at high A and thus $\alpha < \alpha_0$ in the very forward region. Indeed, the leading particle is expected to loose more energy when travelling through the heavy nucleus [20].

(c) The target fragmentation region ($\alpha \gtrsim 1$) is simply explained by assumption of successive interactions of the projectile [10] which thus produces $\bar{\nu}_A$ times more particles than in scattering from hydrogen.

Thus qualitatively everything follows from the general idea of long time scale of hadronic production as expressed in Eq. (2.3). This is of course quite an important finding, but can one go further and learn more?

To illustrate the problem, let us consider in more detail the process of subsequent interactions of the projectile with the target, in particular the physical situations which lead to the two limiting cases $\alpha = \alpha_0$ and $\alpha = 1$.

The condition $\alpha = \alpha_0$ means that the multiplicity of the produced particles does not depend on the number of collisions of the projectile in the target nucleus. Such situation arises if the high-energy interactions are truly of short-range character in rapidity. Then the particle production in the central region of rapidity is independent of the projectile and the target.

For $\alpha = 1$ the multiplicity is proportional to average number of collisions. This suggests a simple picture of "leading particle cascade" [21] where in each collision the incident projectile produces the same number of particles as in the collision with free nucleon. The total production adds up so that one obtains $\bar{\nu}_A$ times the elementary multiplicity.

We have seen that the data do not correspond to any of these limiting cases, but rather interpolate between them. The main problem in the description of single-particle spectra is thus to find a physically acceptable mechanism which provides a correct interpolation formula for

$\alpha = \alpha(y)$.

Let me stress again: qualitatively the problem is essentially understood. What is needed is the precise quantitative description. Several attempts of such quantitative analysis were developed. One of the most popular is based on Reggeon Field Theory which was applied to hadron-nucleus collisions by many authors [22-28]. Another idea was to use the "non-interacting fireballs model" or "realistic leading particle cascade" i.e. leading particle cascade with energy conservation taken properly into account [29-31].

I shall not discuss these investigations here for two reasons: (a) they were covered already by speakers on previous multiparticle meetings and (b) they tend to ignore the specific internal structure of the projectile by emphasizing those general features of the data which can be explained without referring to this structure. While this is an interesting problem, it clearly goes beyond the scope of the present talk.

Let us now see on an intuitive example [32] how the composite structure of the hadronic projectile can influence the A-dependence of particle production.

Consider a hadron h composed of N constituents which can interact independently with the target. The total number of particles produced at given rapidity y is then a sum of the contributions from collisions of individual constituents with the target. Since the number of constituents which interact when projectile h passes through a heavy nucleus is obviously larger than the one in collision with hydrogen, one obtains increase of multiplicity with increasing A, i.e. $\alpha > \alpha_0$. This is illustrated in Fig. 3. On the other hand, the number of interacting constituents is most likely smaller than the total number of collisions of the projectile with the target, i.e. $\alpha < 1$. Thus indeed, the composite character of the projectile implies an interpolating situation $\alpha_0 < \alpha < 1$ as required by the data in central region of rapidity.

In this picture, the detailed value of α depends on specific dynamical assumptions about the number, distribution and properties of the constituents. Therefore the detailed comparison with the data may give information about them. In the following sections we shall discuss this in more detail.

2.4. Constituent quarks

A simple model which illustrates the general idea was proposed in Ref. [32]. It was assumed that incident hadron is composed of N constituents which interact independently with the target. Furthermore, it was assumed that interaction of a single constituent with the target satisfies the principle of short-range order, i.e. it is independent of the target in the central region of rapidity. With these assumptions the prediction of the model is (in the central rapidity region)

$$R \equiv \frac{1}{\sigma_A} \frac{E d\sigma_A}{d^3p} \Big/ \frac{1}{\sigma_H} \frac{E d\sigma_H}{d^3p} = \frac{\bar{\nu}_h}{\bar{\nu}_c} \qquad (2.5)$$

where $\bar{\nu}_c$ is the average number of collisions of the constituent c in the target nucleus. The numerical value of R depends thus on the cross-section of the constituent, that is on the number of the constituents in the projectile. This is shown in Fig. 5 for nucleon-nucleus scattering [32]. One sees that the prediction is [illegible] sensitive to the number of constituents and that the neutron-nucleus data from Ref. [9] clearly indicate $N = 3$ as a preferable choice [13]. When translated into formula (2.4), the Eq. (2.5) gives $\alpha = .84$ which is close to the value observed in Ref. [12], as seen in Fig. 3.

It is tempting to interpret this result as evidence for the presence of three well-defined constituent quarks inside the nucleon [33, 34, 35], giving further support to the existence of important correlations between partons inside the hadrons (two-step structure, Ref. [36]). Indeed, independent production by all partons would correspond to $N = \infty$ and thus to $R = \bar{\nu}_h$ in strong disagreement with data. It follows that in the process of particle production the partons act collectively in groups i.e. they are clustering around the valence quarks.

Further support to the constituent quark model of hadron-nucleus interactions was given in Ref. [37] where the fragmentation region of the projectile was discussed. The argument runs as follows. It is assumed that the momentum spectrum in the projectile fragmentation region is determined by "spectator" quarks which did not interact i.e. that the interacting constituent quark looses most of its energy into production of secondaries . The number of such quarks obviously decreases with increasing nuclear number of the target (by the argument illustrated in Fig. 5). This gives qualitative explanation for $\alpha < \alpha_0$ in the forward region of Fig. 3. The authors of Ref. [37] analysed the proton and meson spectra in fragmentation region and showed that they agree with data on proton-nucleus interactions at ~20 GeV [38]. It would be very interesting to extend this analysis to higher energies. •

At this point it should be stressed that the production mechanism suggested by the constituent quark model and described above is very different from the one adopted in recombination models developped recently [39-41]. In the recombination models three valence "bare" quarks are not influenced by the interaction and thus conserve their energy and momentum during the collision. The observed hadron spectra in the projectile fragmentation region are thus expected to be essentially independent of A [42], i.e. $\alpha = \alpha_0$. Thus it seems that some modifications of the recombination models are necessary in order to account for nuclear attenuation of particles in this region1/.

As we have seen, the attenuation of fast particles is very natural in the constituent quark model [34]. The detailed quantitative predictions depend, however, on details of quark-quark interaction, in particular on the inelasticity coefficient in qq collisions..The results of Ref. [34] suggest that this inelasticity coefficient is close to 1, i.e. that almost all the energy of the constituent quark is lost during the collision. It seems to me that further experimental and theoretical investigations of this question are possible and should lead to a good determination of parameters of qq scattering.

To summarize, the constituent quark model is supported by the data from nuclear targets. As it is also theoretically desirable for explanation of deep inelastic hadronic and leptonic processes [36] and of standard low transverse momentum hadronic collisions [33-35], it deserves, in my opinion, very serious attention. The model has many potential possibilities of further qualitative predictions including also nucleus-nucleus collisions2/. The decisive test shall probably come from detailed studies of quantum number correlations which are characteristic for all quark models.

2.5. Two-phase models

A presently accepted model of hadrons depicts them as made of many partons, i.e. point-like constituents. It is therefore interesting to investigate the consequences of this picture for hadron-nucleus collisions [44,45]. The simplest possibility is the so-called two-phase model [44] shown in Fig. 7.

After the first collision the incident hadron turns into an incoherent collection of point-like partons. The cross-section for interaction of a high-energy parton with nuclear matter is very small (behaves as E_{lab}^{-1}) and thus the parton can not interact again (that is, produce a cascade) unless it develops a tail of low-energy partons, i.e. after it becomes the ordinary hadron.

The crucial parameter in this model is the parton life-time in the laboratory frame $t = \gamma t_o$, where γ is the parton Lorentz factor and t_o is the life time in the parton rest frame. We see that t determines the fraction of partons which, at given energy, turn into hadrons inside the nucleus and can cascade. Numerical estimates of t indicate that, if this mechanism is fully responsible for the observed increase of the multiplicity, t_o should be rather short: $t_o \lesssim \frac{1}{100 m_\pi}$. Interpretations of such a surprisingly short life-times were given in Ref. [44].

In the simplest version described above the two-phase model predicts that for the very fast secondaries, satisfying the condition $t \gg 2R$ where R is the nuclear radius, the spectrum should not depend on A [42]. As we have already seen, this contradicts the data (unless the situation changes at higher energies). One should thus consider a more complicated picture, taking into account fluctuations of parton number inside the incident hadron [22b, 46]. Such fluctuations can explain qualitatively the increasing multiplicity of secondaries in central region and consequently the increasing energy loss in the projectile fragmentation region with increasing target thickness. However, the predictive power of such a scheme is very limited. Indeed, before one obtains a better understanding of the characteristic time t_0 one cannot even conclude that cascading effects are necessary to describe the data. Taking the conservative point of view, one may say that some cascading of secondaries should be present at least in the target fragmentation region and thus the two-phase model can possibly be useful for description of the data there. The best way to test the model and to determine t_0 is to measure directly the amount of intra-nuclear cascading of secondaries for different regions of rapidity. Such measurements of cascading would be particularly interesting since the value of t_0 is clearly of importance for understanding hadron structure and elementary interactions between partons. A possibility of such a measurement is discussed in the next section.

2.6. Conclusions and proposals for further experiments

We have seen in the preceding sections that the A-dependence of particle production from nuclear targets is sensitive to the internal structure of the projectile. The present data support the constituent quark model, i.e. the clustering of the gluons and $q\bar{q}$ sea pairs around the valence quarks [33-35]. To test this picture further, one would need better information on the following issues:

(a) Amount of intra-nuclear cascading,

(b) Spectra of different particles in the projectile fragmentation region and their correlations with the associated multiplicity in central region,

(c) Quantum number correlations between the projectile and particles produced in the projectile fragmentation region. This should show characteristic features of the quark model (e.g. different A-dependence for favoured and unfavoured reactions).

The last two points are readily accessible for experimental investigation and some new experiments are under way [47]. One may perhaps think of extending them to higher energies in order to separate better the fragmentation regions of target and projectile. In this context let me remark that the experiments with heavy ions at storage rings seem feasible and would be particularly effective. They could at the same time test the extension of the existing models to nucleus-nucleus collisions.

An experiment to measure directly the amount of intra-nuclear cascading was proposed recently [48]. It was suggested to measure the photoproduction of particles associated with the fast vector meson in the final state. According to vector dominance model the photon changes into a vector meson which travels through the nucleus and interacts as a normal hadron. By triggering on different vector mesons, one can thus select interactions with very different number of collisions inside nucleus, as seen in Fig. 1. In particular, when triggering on heavy vector mesons ψ or Υ the number of collisions, even for heavy nuclei, is close to 1. Thus any substantial increase of associated multiplicity with nuclear number A must be due to intra-nuclear cascading which is therefore measurable in such a process. Another interest in this experiment is that it should provide very clean leading particle spectra. Indeed, the vector mesons ϕ , ψ and Υ once created are unlikely to change into other particles when travelling through the nucleus because of IOZ rule . In this respect they are much better than nucleons and pions. Finally, these measurements could perhaps help in understanding the anomalous behaviour of absorption cross-section of high--energy photons [49].

3. High transfer phenomena

3.1. Motivation and phenomenology

According to the present believes, in the high-transfer ("hard") processes one observes direct interactions of elementary hadronic constituents (partons). A simplest example is deep-inelastic leptoproduction.

Schematically, the process proceeds in two steps: (i) a parton (quark) is struck out of the hadron; (ii) the parton decays into observed hadrons. From the studies of lepton--nucleon interactions one has a fairly good knowledge of the first process. However we are rather ignorant about the mechanisms of parton decay (which is additionally complicated by the interaction with the rest of the hadron as required by the principle of confinement). A particularly intriguing question is the time-scale of this decay process.

Two extreme possibilities can be considered: "hadronization" of a parton may be a long process with the characteristic time proportional to the parton energy; or it may happen that the peculiar character of the confinement forces implies fast change of the parton into hadrons, independently of its energy. In the commonly accepted picture of hard processes [50-52], the first option is chosen: the fast parton kicked off the hadron behaves as a "quasi-free" particle, i.e. its decay is practically independent of the rest of the process. This picture suggests that indeed a fast parton decays far from the interaction region, i.e. it conserves its identity for a rather long time before the confinement forces start to operate effectively.

In such a case the experiments with nuclear targets give us opportunity to study the interaction of the partons with nucleons of the target nucleus. This is illustrated in Fig. 8, again for leptoproduction: the quark, produced from one of the nucleons, travels through the nucleus and can interact with other nucleons. This final-state interaction can be estimated by studying the A-dependence of the process.

The starting point in the phenomenological discussion of the A-dependence of hard processes is the formula

$$d\sigma_A = A \, d\sigma_H \tag{3.1}$$

suggested by the short-time character of the reaction and its small cross-section [53]. The interesting physics is thus contained in deviations from the formula (3.1) which are the main concern in the analysis of the data. As an illustration we show in Fig. 9 the data from Ref. [54], where the exponent α (Eq. (2.4)) describing A-dependence of single-particle spectra in proton-nucleus collisions is plotted versus transverse momentum of the produced particles. One sees indeed quite strong deviations from $\alpha = 1$ at large values of p_t.

Such deviations can possibly arise from three different physical processes:

(a) The final state interactions in the nucleus, as discussed at the beginning of this section.

(b) The nuclear structure at short distances may be more complicated than normally expected. In such a case the simple relation (implicit in the Eq. (3.1))

$$N_A(x_B) = A \, N_H(x_B) \tag{3.2}$$

may be not satisfied [55],[56] at least for some values of the Bjorken variable x_B. Here N_A and N_H are parton densities in nucleus and nucleon, respectively. Violation of Eq. (3.2) means that nucleus cannot always be treated as a collection of quasi-free nucleons.

(c) For some kinematic configurations (to be discussed in the next section) the shadowing effects [51],[57] may be not negligible.

Thus the natural first step in the phenomenological discussion of the data is to separate the effects of different physical origin. This can be achieved by comparing different processes: leptoproduction, production of lepton pairs and high p_t production [55,56].

The analysis of the existing data (presented in the next two paragraphs) indicates that nuclear structure and shadowing effects (points (b) and (c) above) are unlikely to explain the large deviations from Eq. (3.1), as seen e.g. in Fig. 9. Consequently, the dominant origin of such deviations is most probably the final state interaction of the hadronic constituents produced in the first hard collision with the nucleons in the target nucleus. This is a lucky situation - a most interesting process is the dominant one and therefore comparatively easy to study. It is just this circumstance which allows to be optimistic about the possibilities of nuclear interactions in revealing the hadronic structure.

3.2. Time scales and distances involved in hard processes

The important point in the two-step picture of hard processes outlined in the previous paragraph is the assumption that the first step is of short-time character, as opposite to the second step "hadronization" which takes a rather long time. For analysis of experiments with nuclear targets this short-time character of hard processes is of crucial importance because it determines the longitudinal distance in which the process takes place. In particular, if the relevant distance is shorter than 1 fermi, one may safely accept that only one nucleon was involved in the hard process. Otherwise one has to take into account the possible collective phenomena, e.g. the shadowing effects.

Let us see how the kinematic conditions determine the time scales and distances [51] involved in leptoproduction and in production of lepton pairs.

(a) Leptoproduction. In electroproduction the time scale is given by the life time of the virtual photon

$$t = \frac{1}{E - E' - E_\gamma} \approx \frac{1}{M x_B} \simeq \frac{1}{5 x_B} \text{ fermi} \qquad (3.3)$$

where M is the nucleon mass and $x_B = \frac{Q^2}{2M\nu}$. The variables E, E' and E_γ are energies of initial and final electron and of virtual photon; Q^2 is the four momentum transfer squared and $\nu = E - E'$.

If one requires that no more than one nucleon participates in the process, one obtains the following condition:

$$t \lesssim 1 f \quad \Rightarrow \quad x_B \gtrsim .2 \qquad (3.4)$$

The same conditions are also valid for neutrinoproduction.

It follows from Eq. (3.4) that in leptoproduction processes the nuclear shadowing effects can appear only in small x_B region and should disappear for $x_B > .2$.

(b) Production of lepton pairs

Here the time scale (and the longitudinal distance involved) is determined by the life-time of the $q\bar{q}$ system before its decay into a lepton pair. In the rest frame of the pair this time is given by

$$t_0 \simeq \frac{1}{M_{ee}} \qquad (3.5)$$

where M_{ee} is the invariant mass of the pair[3/]. In the laboratory frame we thus have

$$t = \gamma_{ee} t_o = \frac{x_{lab}}{10\,\tau} \qquad (3.6)$$

where $x_{lab} = E_{ee}/E_{lab}$ and $\tau = M_{ee}^2/s$ are the scaling variables. Here E_{ee} is the energy of the pair in the laboratory frame, E_{lab} is the incident energy and s is the total c.m. energy squared.

It follows from Eq. (3.6) that the condition for interaction with no more than one nucleon is[4/]

$$t' \lesssim 1f \implies \tau \gtrsim x_{lab}/10 \qquad (3.7)$$

The condition similar to (3.7) should be applicable also to large p_t production. However, in this case the measurement of variables corresponding to x_{lab} and τ is much more difficult as they refer to final jets rather than to leptons.

3.3. Number of partons in the nucleus

The measurements of total leptoproduction cross-section on nuclear targets [58] are schematically shown in Fig. 10 where the exponent α from the formula (2.4) is plotted[5/] versus $x_B' = Q^2/(Q^2 + W^2)$. Since the total leptoproduction cross section is proportional to the number of partons in the target as seen by the incident lepton, and is independent of final state interaction , the Fig. 10 gives immediately the deviation of this number from the simple formula (3.2). One sees that the observed deviations are very small indeed, except in the closest neighbourhood of $x_B = 0$: α is rather close to 1 for $x_B > .05$.

In the region $x_B < .05$ the values of α are significantly below 1. This can be interpreted as shadowing effect[6/] which, as we have seen in the preceding paragraph, is actually expected to show up in this region [51],[57]. The Vector Dominance model predicts even more shadowing [59] (full line in Fig. 10) and is inconsistent with data [49].

Thus the general conclusion from the data shown in Fig. 10 is that, if there exist deviations from the formula (3.2) they are very small and do not contradict the idea that the nucleus can be treated as a collection of quasi-free nucleons.

This conclusion is confirmed by the data on A-dependence of the lepton pair production. Here α is consistent with 1 for $\tau \gtrsim .1$ and $\alpha < 1$ in the region $\tau \approx 0$. Again, as discussed in Section 3.2, for $\tau \approx 0$ the produced virtual $q\bar{q}$ state lives long enough so that one expects some shadowing in this region.

To summarize, the nuclear structure does not introduce significant complications. Consequently, apart from possible shadowing effects which should be fairly easy to identify, most of the A-dependence observed in large transfer processes originates from the final state interaction inside the nucleus. Thus indeed the nuclear experiments appear to be a very good tool for studying the interactions of partons inside the nuclear matter.

3.4. Final state interactions in leptoproduction

Leptoproduction is a particularly clean case for studying the final state interactions because the struck-off parton is expected to be a quark with definite energy and momentum (determined from the momenta of the initial and final leptons). One thus obtains a sort of "tagged" beam of quarks interacting with nucleons in the target nucleus. Such well-defined initial conditions simplify substantially the analysis.

Let us now discuss some possibilities of interaction of an energetic quark produced from one of the nucleons and travelling through the nucleus, as illustrated in Fig. 3.

(a) Annihilation of the (anti) quark with one of the quarks in the target and formation of a low mass meson. The characteristic features of this process are (a) its sensitivity to the quantum numbers of the produced mesons and (b) the momentum of the produced meson is to a good approximation equal to the momentum of the interacting quark. Its presence would thus strongly modify the A-dependence of the structure of jets observed in leptoproduction from nuclei. On the other hand, annihilation cannot change the jet cross-section. Thus it can be easily identified by comparing A-dependence of single particle spectra and of jet cross-sections. Theoretically, this process should decrease rather fast with increasing energy of the quark and thus it is unlikely to play a significant role.

(b) Hard scattering of the quark. Here the characteristic feature is the production of two jets in the current fragmentation region approximately aligned along the direction of the initial quark. Since the exchange of quantum numbers is unlikely (gluon exchange!), at least one of the jets should have the same structure as the one produced by the original quark. The identification of such two-jet processes would thus give direct measurement of hard quark--nucleon scattering[7/].

(c) Multiple soft scattering of the quark with possible emission of soft gluons. This process is very difficult to estimate theoretically[8/]. However, since the total cross--section for interaction of an energetic point-like quark with nucleon is presumably very small, the standard prejudices suggest that multiple scattering is negligible and thus the effect should disappear for high quark energies[9/]. For lower energies the life-time of the quark may be short enough to allow the decay into hadrons inside the nucleus.

This would produce significant cascading phenomena, probably easy to identify, thus allowing the measurement of the quark life-time [60].
Thus the summary of the theoretical expectations is as follows: For the high energy quark there is essentially only one possibility left, namely hard scattering from one (or more) nucleons in the target. This leads to a clear-cut prediction that any significant A-dependence in the *current* fragmentation region must be associated with two-jet structure of the events.

Such a situation is expected asymptotically, at very high quark energies. To face the reality we have to consider also, however, what kind of effects can destroy this simple picture at lower quark energies. One was discussed already, the quark decay inside the nuclear matter. Another one is the possible interaction of the "colour polarization cloud" [51] which is formed together with the high-momentum quark struck-off by the lepton. Such a polarization cloud (made of gluons and $q\bar{q}$ pairs) travels together with the high-momentum quark (to neutralize finally its colour) and accelerates along the way. Thus it can reach energies up to 20 GeV within a heavy nucleus and produce multiplication of particles in the target fragmentation region, similar to that observed in hadronic reactions (where the analogous polarization cloud is formed [51]). Thus even without any final state interaction of the fast quark in the nuclear matter we would expect the additional particle production, distributed in rapidity as shown schematically in Fig. 11. The effects of final state interaction should be thus looked for at rapidities above the ones corresponding to target fragmentation region, i.e. above 3-4 units. Consequently, the required energy of the quark should be well above 50 GeV.

Another problem one should take care of is that, for small x_B, the reaction can proceed (at least partly) by a generalized vector dominance mechanism. In such a case the interaction is caused by a hadron-like $q\bar{q}$ system and, consequently, should be similar to hadron-nucleus collisions. As discussed in Section 3.3, this effect should disappear for $x_B > .2$.

From the existing data one has a limited information on A-dependence of the single particle spectra. In Fig. 12 the average multiplicity produced in emulsion by 150 GeV muons [61] is compared with that obtained from hydrogen target. One sees clearly a multiplication of particles over the whole range of the Bjorken variable $\omega = \frac{1}{x_B}$. The pseudo-rapidity distribution of the particles produced in the same experiment are compared in Fig. 13 with those produced by protons and pions at the energy approximately corresponding to the average energy transferred by the scattered muon to the target. The spectra are similar, but one sees a difference in the central region where the production by muons is significantly smaller from that by hadrons. In Fig. 14 the projectile fragmentation region measured in electroproduction experiment [62] is shown. A clear attenuation of fast particles is observed, slightly weaker than in hadronic interactions shown in Fig. 3.

Thus the existing data hardly show any characteristic feature which would be qualitatively different from the ones observed in low p_t hadron-nucleus collisions[10/]. One is therefore forced to conclude that either (a) the fast quark does indeed interact with nucleus similarly as a normal hadron, or (b) in the data shown in Fig. 12-14 the specific quark interactions are masked by other effects.

Since the first possibility appears rather revolutionary, the second one should be quite carefully studied. Indeed, one cannot exclude that what one sees in Figs 12-14 is mainly the interaction in the nuclear matter of the "colour polarization cloud" described before. The rapidity range available in the experiments [61-63] is not large enough to decide conclusively (target fragmentation region extends to more than half of the available range in Ref. [61], and even further in Ref. [62] and [63]). The crucial point is what happens with increasing energy of the quark: will the multiplication extend to higher rapidities, or will it stay confined to the target fragmentation region. An experiment which would clear up these problems is thus badly needed.

To summarize, there is no evidence in the present leptoproduction data for any specific features of the interaction of a fast bare quark in nuclear matter. It may be argued, however, that higher quark energies are necessary in order to see clearly such effects. It seems thus worthwhile to study this problem at highest possible ν and for $x_B > 0.2$, where the pattern of the data is expected to change and thus to be qualitatively different from the one observed in hadron-nucleus reactions at low p_t. If such change of pattern is not observed, the presently accepted ideas about confinement mechanism and interactions of bare quarks should be rather profoundly reexamined.

3.5. Final state interactions in large p_t processes

The strong A-dependence of hard processes (Fig. 9) was originally discovered in large p_t production [19],[54]. This finding was immediately interpreted by many authors [64-67] as the effect of final state interaction in nuclear matter. However, the quantitative analysis of large p_t data is quite difficult, mainly because the mechanism for elementary hard collisions is not yet well understood [52],[65],[68]. Consequently, it is not clear what partons (or groups of partons) are interacting in nuclear matter. Whatever the case, it is certain that the final state interactions are more complicated than in case of leptoproduction. Thus it seems to me that there is very little chance of quantitative understanding of large p_t phenomena in nuclei before one clears up the situation in leptoproduction. A very promising approach, however, is the simultaneous investigation of large p_t phenomena and leptoproduction with the hope to learn about the effects which are not easily accessible in leptoproduction alone, e.g. the interactions of energetic gluons in nuclear matter.

In view of this rather complicated situation, it does not seem possible to list all of the arising possibilities. Therefore I restrict myself only to few remarks about implications of the existing data for the relative importance of different processes which may occur in nuclear matter.

(i) In agreement with the theoretical expectations, the annihilation of (anti) quark in nuclear matter does not seem to play an important role. For the proton beam the annihilation mechanism is unlikely to produce large p_t K^- or $\bar{p}$ because the projectile does not contain the relevant valence quarks. The actual calculation [69] shows indeed very little contribution to K^- production from annihilation, contrary to the data shown in Fig. 9 where A-dependence of K^- production is stronger than for other mesons.

(ii) There are no data on event structure and thus the existence of hard parton scattering in nuclear matter is not established. However, the existing data are certainly consistent with the presence of hard scattering, as seen from Fig. 15 [70] where A-dependence of the jet cross-section is shown. The observed strong A-dependence shows that the presence of the nucleus changes not only the jet structure but also the number of jets - as expected in hard scattering mechanism.

(iii) Final state interaction mechanism implies that the A-dependence of a hard process can be represented in the form of the series

$$d\sigma_A = A\left\{c_0 + c_1 A^{1/3} + c_2 A^{2/3} + \ldots\right\} \qquad (3.8)$$

where the consecutive terms are positive and arise from final state interaction with 0,1,2,... nucleons in the target [64-67]. It follows from the Eq. (3.8) that if only one nucleon is involved in the final state interaction, α cannot exceed the value 4/3. A glance on the data in Fig. 9 shows that this condition is very well satisfied for π^+, π^- and K^+ production. However, for K^-, p and $\bar{p}$ the limiting value is reached and even exceeded. This strongly indicates the presence of more complicated final state phenomena involving at least two nucleons from the target.

(iv) The data show an anomalously large enhancement of proton production in the presence of nuclear matter (for proton beam). This indicates existence of additional mechanism. In view if the remark (iii), a natural candidate is the hard scattering of more than one valence quark of the projectile from different nucleons in the target nucleus as illustrated in Fig. 16. This can explain a large value of α and is also consistent with the present ideas on large p_t baryon production in elementary collisions [64,70].

(v) The strong A-dependence of K^- and $\bar{p}$ production is difficult to interpret. It might also be caused by hard scattering of several (anti) quarks from different nucleons in the target.[11] However, it is not clear why such effect should not appear for other mesons as well. I feel that only careful quantitative comparison of the contributions for all produced particles can settle the problem. Also the comparison with leptoproduction (where such process is not expected to take place) should be helpful.

(vi) As we have seen, the leptoproduction data show fairly strong multiplication of particles in the target fragmentation region. One could thus worry about the effects of the "polarization cloud" also in case of large p_t processes. Fortunately, for small laboratory angles (below 100 mrad) these effects should be concentrated at relatively low transverse momenta - below 1.5 - 2 GeV - and thus can be separated out.

To summarize, similarly as in leptoproduction, also in large p_t physics there is no definite evidence for the most characteristic final state interaction, i.e. the hard scattering of the fast bare quarks. Strong nuclear enhancement of baryon and antibaryon production indicates actually that the dominant effect is the interaction of groups of partons with several nucleons in the target. Thus it might be not very easy to separate out the really elementary processes. Here again, the necessity of detailed comparison with leptoproduction data is evident.

3.6. Conclusions

The common ideas about the elementary hard processes imply the existence of the final state interaction of quasi-free bare partons in nuclear matter. We have seen that the existing data on leptoproduction and high p_t phenomena do indeed indicate the presence of final state interaction effects. The characteristic features of the data do not seem to correspond, however, to the expectations one has about the interaction of quasi-free bare partons. It is not entirely clear whether this is due to the limitations in accuracy and kinematic range of the available data, or should be rather considered as indication of unexpected aspects of parton physics. Further progress depends crucially on resolution of this problem in future experiments. Two points are of particular interest: (a) does the multiplication of particles observed in Refs [51] and [63] extend beyond the target fragmentation region, and (b) can one find evidence for hard scattering of quasi-free bare partons. Both these questions can best be answered by precise leptoproduction experiments at highest possible ν and $x_B > .2$, measuring both low- and high-transverse momentum particles (with respect to direction of the exchanged current).

It is obvious that the answer to these problems has immediate consequences also for elementary interactions. These consequences can be actually quite dramatic, should the nuclear experiments contradict the existence of quasi-free fast bare partons in the final state of the elementary hard process. It seems however too early to speculate further about this possibility.

Acknowledgements

Most of the material presented in this paper was prepared in collaboration with W. Czyż to whom I thank for constant help and encouragement. Thanks are also due to B. Andersson, J. Bjorken, W. Furmański, R. Hołyński, H. Lubatti, D. Morrison, N. Nikolaev, J. Pišut and K. Zalewski for helpful discussions. Finally I would like to thank to J. Pišut, V. Šimak and M. Šuk for kind hospitality at Tabor.

Footnotes

1/ In view of this, the estimates of the "enhanced $q\bar{q}$ sea" [41] should be reexamined.

2/ For collisions of two nuclei with nuclear numbers A and B, the multiplication in the central region is given by the formula $R = \bar{\nu}_{AB}/(\bar{\nu}_{CA}\ \bar{\nu}_{CB})$ [32]. Here $\bar{\nu}_{AB} = AB\,\sigma_A\,\sigma_B/\sigma_{AB}$ is the number of collisions underwent by nucleons in projectile and in the target, whereas $\bar{\nu}_{CA}$ and $\bar{\nu}_{CB}$ are the number of collisions of the constituent quark in nuclei A and B, respectively. This formula is consistent with the cosmic ray data [43].

3/The transverse momenta are neglected, to simplify the discussion.

4/We neglect for simplicity the correction from velocity of the pair being smaller than c. This effect is negligible in practice.

5/The figure is adapted from Ref. [49].

6/Another point of view was expressed in Ref. [55] where the fine structure seen in Fig. 10 was discussed in detail. It was argued that at high Q^2 there is no shadowing at all and thus the data shown in Fig. 10 measure the actual number of partons in the nucleus. It then follows from energy conservation that if $\alpha < 1$ for $x_B \approx 0$, there exists another region (not far from $x_B = 0$) where $\alpha > 1$ ("antishadowing"). Such effect is indeed indicated by the data of Fig. 10, although the large errors do not allow to make a definite statement. Whatever the case, it is clear that the effects discussed, although certainly important for understanding the underlying physics, are very small indeed and do not contradict the general picture that the strong A-dependence observed in some hard processes (see e.g. Fig. 9) must originate from final state interaction. Let me also mention at this point that the ideas of Ref. [55] can be tested by comparing the function $\alpha(x_B)$ from Fig. 10 with the function $\alpha(x_B = x_A)$ obtained from A-dependence of the production of Drell-Yan pairs. Here $x_A = .5\{\sqrt{X^2 + 4\tau} - X\}$ and X is the Feynman variable of the pair in the nucleon-nucleon c.m. frame. In the limit of high pair masses and for limited transverse momenta, these two functions are expected to be identical (as they both measure the number of partons in the nucleus).

7/Such interactions can affect the estimates of the number of gluon jets in elementary collisions, if the experiment is performed on nuclear target, as is the case for most of the neutrino data (private communication from D. Morrison).

8/For example, a reliable estimate from QCD would require a non-perturbative treatment.

9/This point of view can be questioned. B. Andersson (private communication) estimates that a fast quark looses significant fraction of its energy when passing through a heavy nucleus.

10/This point was particularly emphasized in Ref. [63].

11/Such multi-quark phenomena seem to be quite natural in the constituent interchange model [68].

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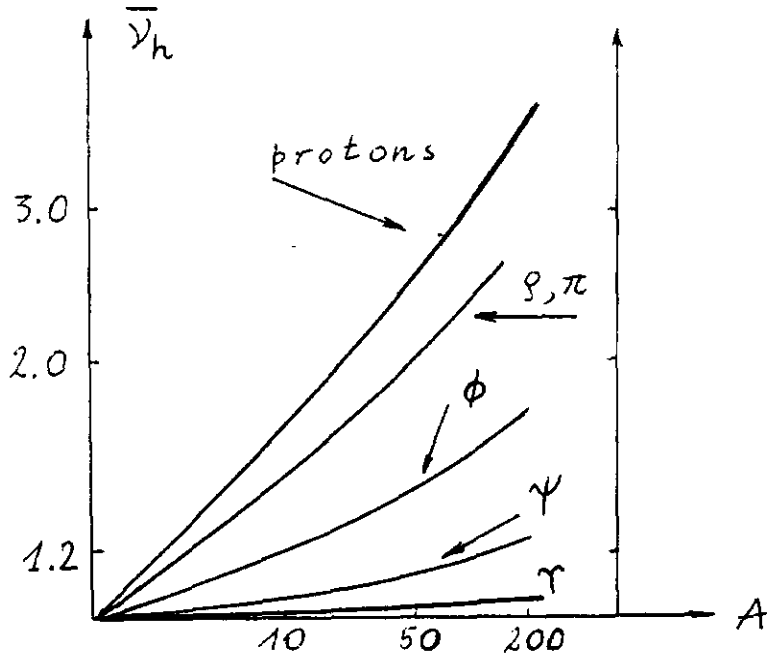

Figure 1. Average number of collisions for different incident hadrons plotted versus atomic number of the target.

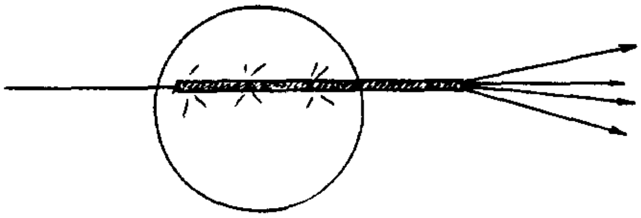

Figure 2. Intermediate state travelling and interacting inside the nucleus.

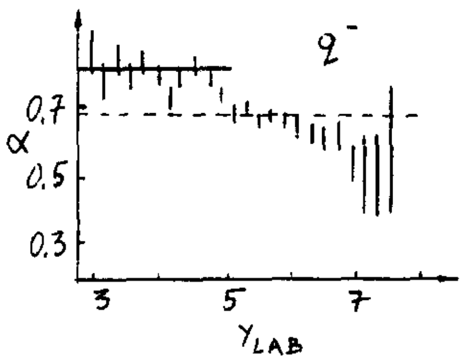

Figure 3. Exponent α from the Eq. (2.4) plotted versus laboratory rapidity of the negative particles produced in 300 Gev neutron-nucleus collisions [12]. Prediction of model from Ref. [32] is also plotted /continuous line/.

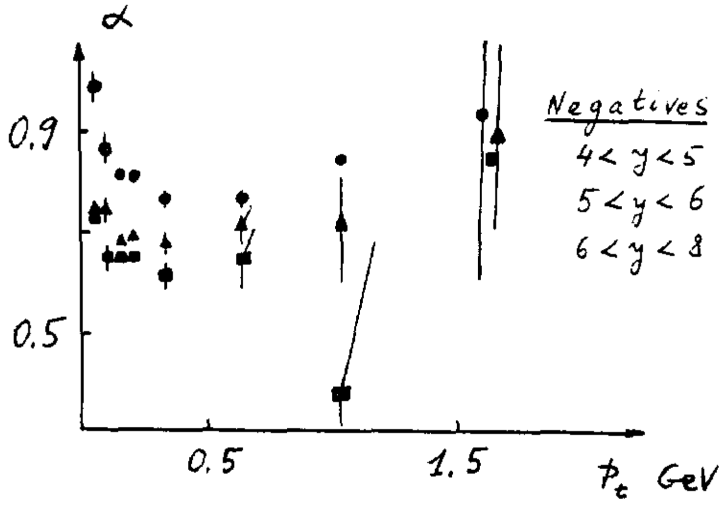

Figure 4. Variation of the exponent α /Eq.2.4 / with transverse momentum of the produced particles [12].

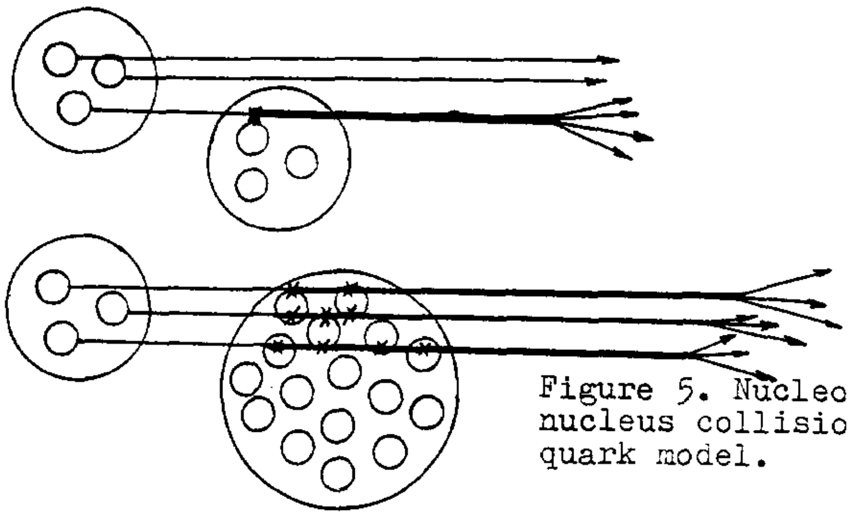

Figure 5. Nucleon-nucleon and nucleon-nucleus collisions in the constituent quark model.

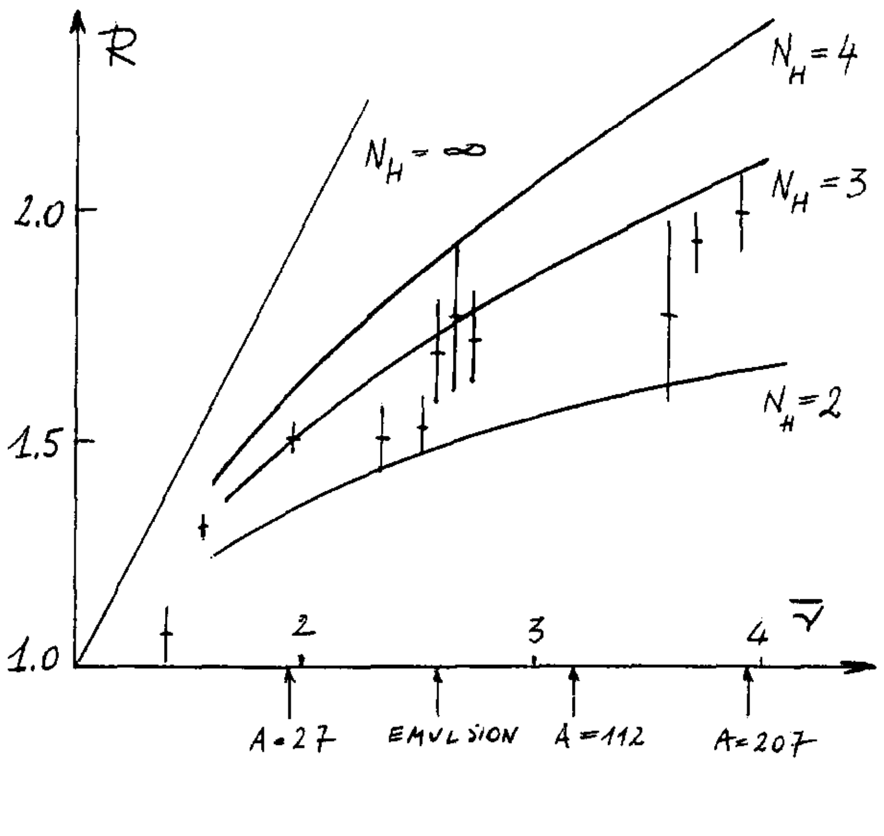

Figure 6. Predictions of the model of Ref. [32] compared with the data of Ref. [9].

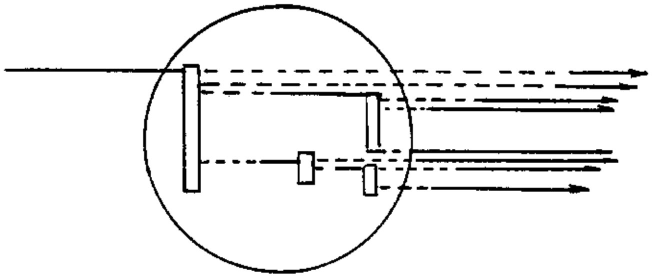

Figure 7. Two-phase model. Dashed lines denote partons. Full lines denote hadrons.

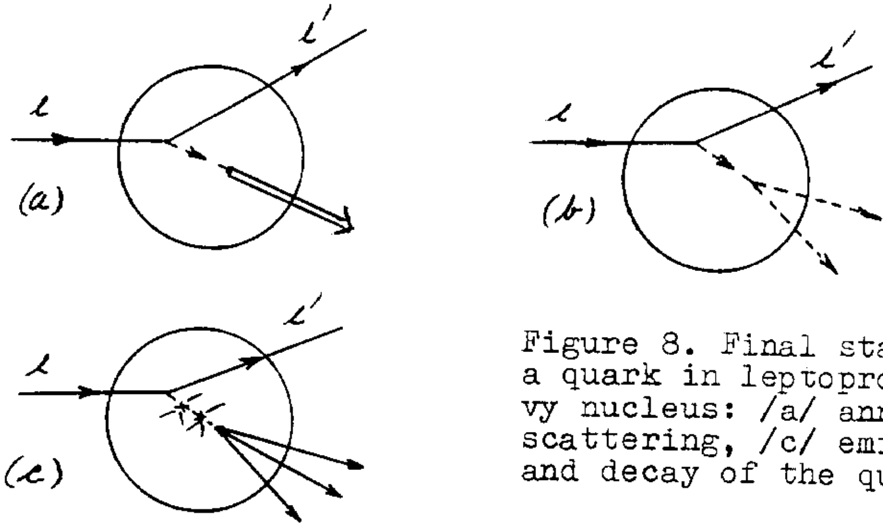

Figure 8. Final state interaction of a quark in leptoproduction from a heavy nucleus: /a/ annihilation, /b/ hard scattering, /c/ emission of soft gluons and decay of the quark.

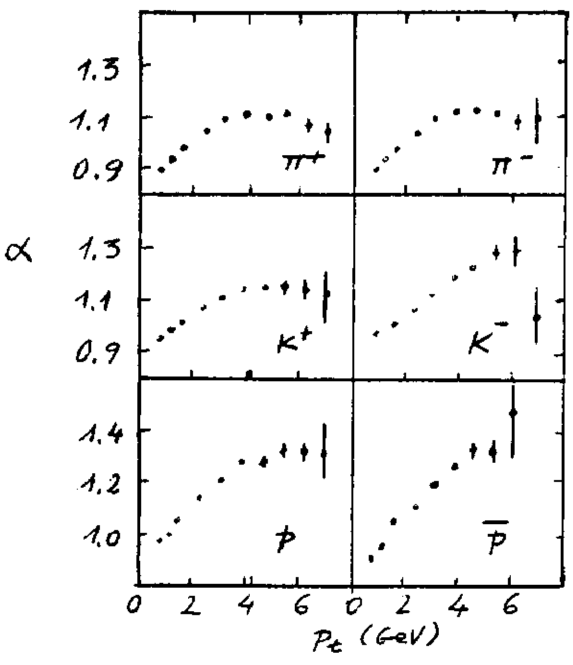

Figure 9.A-dependence of single particle spectra at high p_t [54].

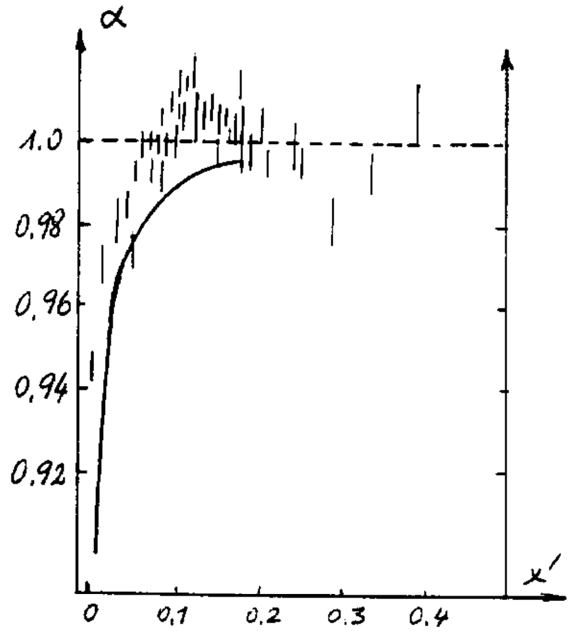

Figure 10. A-dependence of total electroproduction cross-section.

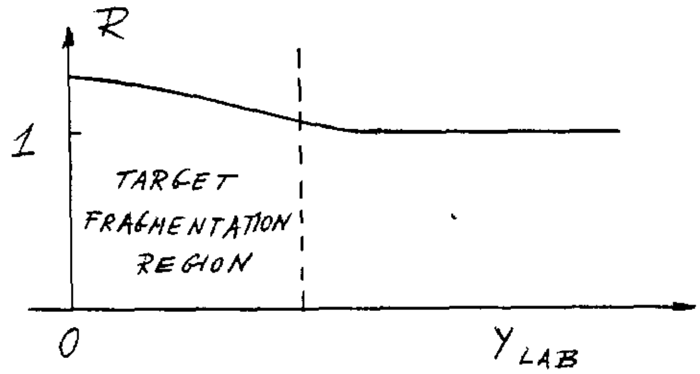

Figure 11.Rapidity distribution of the particle multiplication by the "colour polarization cloud".

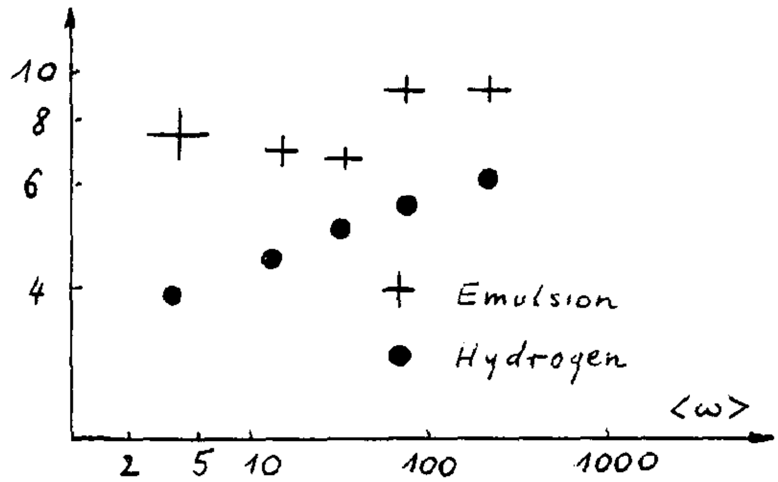

Figure 12.Average multiplicity of particles produced by 150 GeV muons in Emulsion and in Hydrogen[61] .

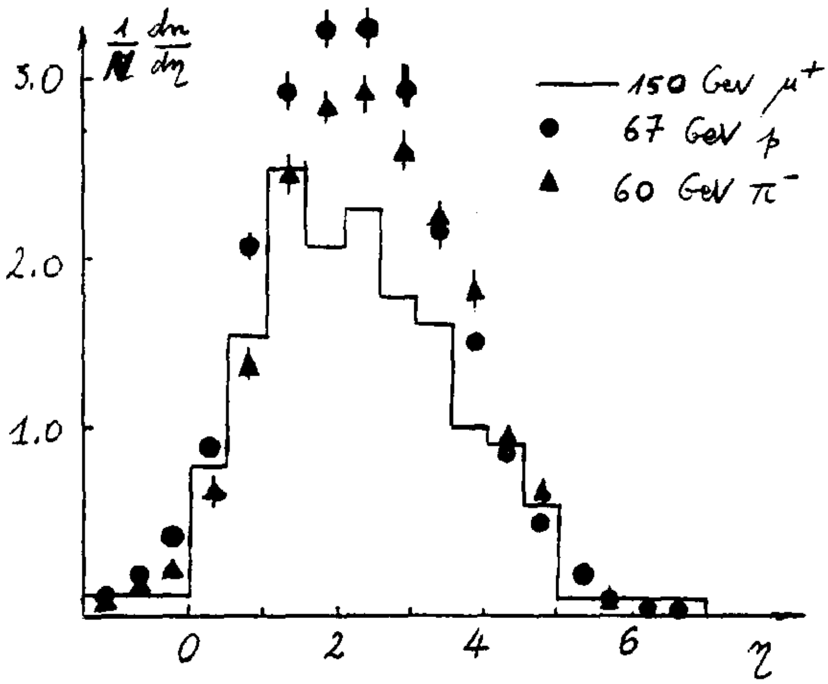

Figure 13. Pseudo-rapidity distribution of particles created in Emulsion by 150 GeV muons, compared with hadron-induced reactions [61] .

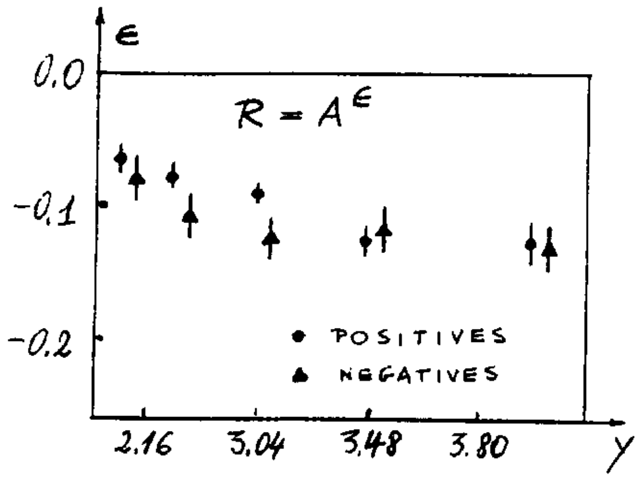

Figure 14. A-dependence of particle production in current fragmentation region [62].

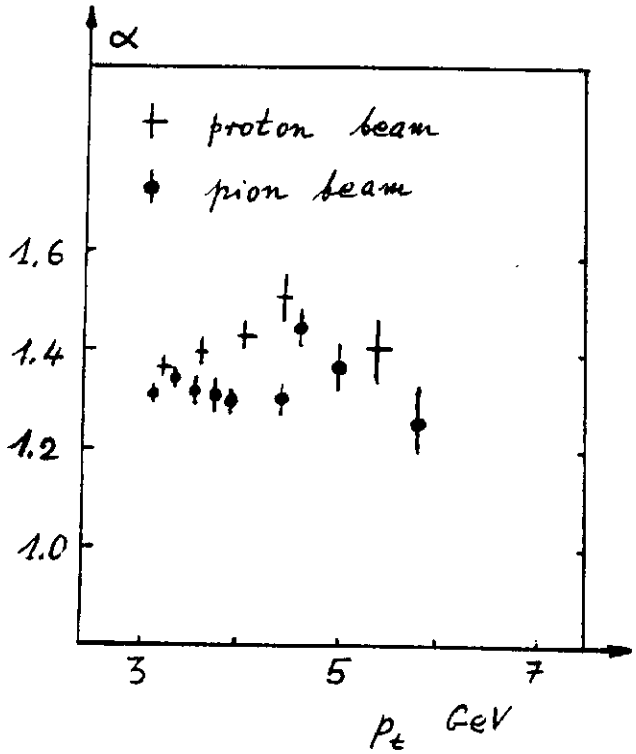

Figure 15. A-dependence of high-p_t jets [70].

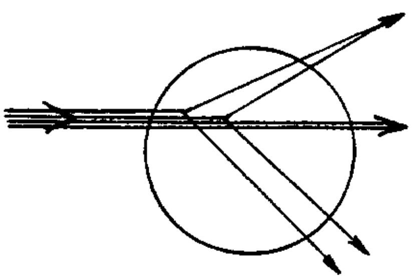

Figure 16. Hard scattering of two quarks from different nucleons in the target.