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Quark Model and High-Energy Nuclear Experiments*

A. BIAŁAS
Fermi National Accelerator Laboratory, Batavia, Illinois 60510
and
Institute of Physics, Jagellonian University, Cracow, Poland

ABSTRACT

Theoretical aspects of the measurements of production of low transverse momentum secondaries in high-energy hadron-nucleus and nucleus-nucleus collisions are discussed. Applications of the quark model to those processes are discussed in some detail.

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I. INTRODUCTION

As was recognized many years ago[1,2] and is now widely accepted, the interactions of high-energy hadrons with nuclear targets provide an opportunity to study the hadronic interactions at very short times. This possibility became particularly exciting, when the experimental discovery of the absence of intra-nuclear cascading of fast secondaries[2-5] indicated that hadronic physics at short distances is far different from what we normally see at macroscopic times. The detailed discussion of this phenomenon in terms of general principles of quantum mechnics and field theory was already presented in several review papers, including the classical one by Gottfried.[6-9] I shall not report the details here, but just indicate the main idea.

First, let me emphasize that the absence of intra-nuclear cascading of secondaries implies that the fast secondary hadrons are created outside of the nucleus. Indeed, were they present inside the nuclear matter, they would interact and induce cascade. This long-time character of "hadronization" can be interpreted as a consequence of uncertainty principle:[1,2,7,10,11] The minimal time necessary to emit a slow hadron is of the order $\tau_0 \approx 1/E_0$, where $E_0 \approx \sqrt{p_\perp^2+m^2}$ is the energy of this hadron. For an observer in laboratory frame this time becomes Lorentz-dilated and the hadron will show up after

$$t \approx \cosh y \, \tau_0 \approx \frac{E}{p_\perp^2+m^2} \tag{1.1}$$

where y'E, p and μ are rapidity, energy, transverse momentum and mass of the hadron. t is very long for typical high-energy, low transverse momentum secondaries. Thus fast hadrons are created well outside the nucleus and, consequently, do not cascade.*

This argument shows that the absence of intra-nuclear cascading is a very natural phenomenon in any theory which contains uncertainty principle—in particular in any field theory.[1,2]

It should be stressed that the absence of intra-nuclear cascading is really of paramount practical importance for all discussions of interactions in nuclei, because it enables a relatively simple interpretation of the experiments and allows possible deductions about elementary hadronic interactions. With cascading present,it would be extremely difficult, if not impossible, to dig out the signal out of noise.

Since we know already that the hadrons are not present in the nucleus, we have to confront the next problem: what is the nature and properties of the intermediate state travelling through the nuclear matter. There is yet no final answer to this question. Actually, this is the "hot" issue at the moment and several different models are being considered.

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*This argument implies also a very specific time-ordering of multiparticle production (slow particles are created earlier than fast ones). For discussion of this point see Refs. 12 and 13.

Most of the models[7,14-26] attempted to describe the existing nuclear data in terms of general properties of hadronic interactions, as derived from high-energy experiments. Thus, in a way, they try to omit the problem of the intermediate state and concentrate on those aspects of nuclear scattering which are independent, or weakly dependent on it. Those investigations showed that, indeed, the gross features of particle production from nuclei can be understood in terms of few parameters describing hadron-hadron inelastic collisions. They played an important role in finding regularities in the data. On the other hand, such a general description has necessarily a limited predictive power.*

Another approach, first considered by Goldhaber[27], and developed independently by several other groups[28-34] emphasizes the relation of the observed A-dependence of the spectra to the structure of the intermediate state which in turn is related to the structure of the incident high-energy hadron. This has the attractive feature that, if indeed such a relation is established, one may use the nuclear data for learning about the structure of high-energy hadrons. In the present talk I shall mostly concentrate on the recent investigations in this direction. I shall argue that, indeed, the nuclear experiments do provide interesting information on the structure of the incident high-energy hadrons.

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*A notable exception is model of Ref. 22.

The intuitive picture which leads to this conclusion is as follows. The incident high-energy hadron can be viewed as a bound state of some numbers of constituents. Consider first its interaction with "elementary" say, proton, target (Fig. 1). In the "soft" — low momentum transfer — inelastic collision this hadronic bound state is destroyed. However, the nature and momentum distribution of hadronic constituents is not expected to change considerably just because the momentum transfer in the collision is small. Thus the constituents continue moving along the direction of the initial hadron, until they change into ordinary hadrons, with the lifetime

$$\tau(\gamma) = \gamma\ \tau_0 \tag{1.2}$$

where γ is the Lorentz factor of the constituent and τ_0 a characteristice lifetime, as measured in rest frame of the constitutent.[12,13]

Consider now the same process happening inside the nuclear matter, as depicted in Fig. 2. In such a case the hadronic constituents move through the nuclear matter and can interact with it. This interaction implies the A-dependence of the process. Thus by measuring A-dependence of final spectra we can obtain information on interaction of hadronic constituents inside the nuclear matter and from that deduce their properties. The important parameter in the description of this final-state interaction is the constituent lifetime $\tau(\gamma)$ given by Eq . (1.2). Indeed, the argument presented here works only for constituents which $\tau(\gamma)$ is greater than nuclear dimension, that is, the energetic constituents. The low-energy constituents have a big chance of decaying into hadrons inside the nucleus and consequently to induce some cascading phenomena inside the nuclear matter. Thus measurements of intra-nuclear cascading of slow secondaries can give information on lifetime of the hadronic constituents. This is an exciting possibility, but its discussion goes beyond the scope of the present paper.

It is worth it to emphasize that in such an approach the nucleus is treated as a part of apparatus — a kind of detector which (due to its extremely high time resolution), 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 the response of our detector. In most applications till now it seems justified to treat nucleus as a collection of quasi-independent nucleons. This description shall be used here.† It should be remembered, however, that, with increasing accuracy of the experiments it may be necessary to go beyond this approximation.

Let me add another remark which seems necessary to avoid misunderstanding. When I talk here about the "constituents"

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*Indeed, the time resolution of a nucleus is of the order of average distance between nucleous $\underset{\sim}{\sim}$ 2fm $\sim 10^{-17}\mu$ sec! This fantastic time resolution is the main advantage of using nuclear targets.

†For other possibilities of treating the nucleus, see Ref. 35.

I do not necessarily mean "elementary constituents", like partons (although I would not like to exclude this possibility, as discussed in the last section). Indeed, the number and the nature of effective hadronic constituents, as seen in low-momentum transfer experiments may be actually very different from the elementary partons seen in deep inelastic processes. This is so because we are testing here hadrons on a very long-term scale compared to the one relevant to the large Q^2 phenomena. Thus we are sensitive to the soft interactions between the partons which may well build up important correlations, e.g., clustering effects. The possibility of uncovering such long-time correlations between partons is one of the attractions of the nuclear experiments at low momentum transfers.

The time available does not allow me to cover also another very exciting subject, namely large transfer processes in nuclear matter. Some aspects of this problem are discussed in Ref. 33 and in contribution of S. Brodsky to this meeting.

The structure of this talk is as follows. In the next section we describe results of a "measurement" of the number of independent high-energy constituents inside the incident energetic hadron.

In Section 3, various tests of the additive quark model are discussed. Nucleus-nucleus interactions are discussed in Sec. 4. In the last section, an attempt is made to interpret the obtained results in terms of the interactions of colored quarks and gluons.

II. MEASUREMENT OF THE EFFECTIVE NUMBER OF HADRONIC CONSTITUENTS

In this section, I shall discuss what the nuclear data can tell about the effective number of constituents contained in the incident hadron. In particular, I shall argue that: (a) the A-dependence of particle production in the central rapidity region is sensitive to the number of constituents in the incident hadron and (b) the data indicate that the effective number of constituents in nucleons and pions is equal to the number of constituent quarks in them, i.e., respectively 3 and 2.

The argument runs as follows.[28] Consider a hadron h made out of N_h independent constituents. The requirement of independence means that we do not like to consider as different the constituents which are strongly correlated to each other.* When hadron h scatters off the hydrogen target, some number (W_H) of these constituents (at least one) undergo inelastic collisions (Fig. 3a), and produce particles. We call them "wounded" constituents. Since the constituents are independent, the observed average multiplicity $\bar{n}_{hH}$ of the production process is

$$n_{hH}(y) = W_H \cdot n_W(y) \tag{2.1}$$

where n_W is the multiplicity produced by one wounded constituent, and y is the rapidity of the observed hadron.

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*This may be considered as a definition of a "constituent".

Consider now interaction of the hadron h with nucleus A. In this case the number of wounded constituents W_A may be substantially larger (Fig. 3b) because the hadron can interact with several nucleons in the target. Consequently, the average multiplicity $\bar{n}_{hA}$ in the production process with nuclear target

$$n_{hA}(y) = W_A \cdot n_W(y) \tag{2.2}$$

is expected to be greater than $n_{hH}(y)$.

For the ratio $R_A(y) \equiv n_{hA}(y)/n_{hH}(y)$ we thus obtain

$$R_A(y) = \frac{W_A}{W_H} \quad . \tag{2.3}$$

The derivation of this formula contains an implicit assumption that production of particles by one wounded constituent is approximately independent of the target. This seems to us a reasonable working hypothesis. Intuitively, it corresponds to the idea that the target can influence the production of only those particles which are created during the passage of the projectile through the target, i.e., only slow particles in the target fragmentation region. Since the bulk of the production in central rapidity region takes place long after the constituent passed through the target, there should be virtually no A-dependence in this region. However, we certainly do not expect the formula (2.3) to be valid in the target fragmentation region. For more detailed discussion of this assumption we refer the reader to the Ref. 27 and Sec. 5.

The right-hand side of the Eq. (2.5) can be expressed by the cross-sections of the constituent. We obtain[28,36]

$$W_A = \frac{N_h \sigma_{cA}}{\sigma_{hA}} \quad ; \; W_H = \frac{N_h \sigma_{cH}}{\sigma_{hH}} \tag{2.4}$$

where σ's are inelastic, nondiffractive cross-sections. Using these formulae we obtain from (2.3)

$$R_A(y) = \sigma_{hH}\sigma_{cA}/\sigma_{hA}\sigma_{cH} = \nu_{hA}/\nu_{cA} \tag{2.5}$$

where ν_{hA} is the average number of collisions of the projectile h in the nucleus A:

$$\nu_h = A\ \sigma_{hH}/\sigma_{hA} \tag{2.6}$$

The only unknown parameter is now σ_{cH}, the inelastic cross-section of the hadronic constituent on hydrogen. However, we know that the hadron h is made of N_h constituents and thus we expect*

$$\sigma_{cH} \simeq \frac{1}{N_h} \sigma_{hH} \tag{2.7}$$

Using (2.4) we obtain immediately $w_H \approx 1$. Furthermore, σ_{cA} can be calculated using (2.7) and the Glauber model formula

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*This relation is only approximate. We have checked that the 10% correction to the formula (2.7) does not change the conclusion of this section. However, they may be not negligible if more detailed analysis of the data is attempted.

$$\sigma_{cA} = \int d^2b \; 1 - \left\{(1 - \sigma_{cH} D_A(b))^A\right\} \qquad (2.8)$$

where $D_A(b) = \int_{-\infty}^{\infty} \rho_A(b,z)\vec{d}x$ and $\rho(\vec{r})$ is the nuclear density. Consequently, we can calculate W_A and R_A in the central rapidity region.

In Fig. 4, the plot of R_A versus ν_{pA} is shown for incident nucleons for different values of number of constituents N_p. The inelastic nucleon-nucleon cross-section was taken 30 mb. The most striking feature one can see in this figure is that, for heavy nuclei, there is quite a dramatic dependence of predicted R_A on the assumed number of constituents N_p in the incident nucleon. It is just this strong N_p dependence which makes possible the determination of N_p from nuclear data. The data from Busza, et al.[35] are also shown in this figure. It is clear that they favor the choice $N_p = 3$, which coincides with the number of quarks inside the nucleon[38,39].

In Fig. 5 we are repeating the same exercise for pion beam. Again R_A is plotted versus $\nu_{\pi A}$ for different N_π. Although the data[5,38] are much more scarce than in the previous case, one can see a clear indication that $N_\pi = 2$, again coinciding with the number of quarks in the pion.

These results are very appealing, because they suggest that in the low momentum transfer phenomena the constituent quarks play the essential role. This could possibly be interpreted as evidence for strong cluster-like correlations between the wee partons and valence quarks. That is to say, the wee gluons and $q\bar{q}$ pairs are not independent, but are clustering around the valence quarks. It should be noticed that such a picture was advocated on different grounds sometime ago by Leningrad group[40,41] and by Cabibbo et al.[41] Another possible interpretation is discussed in the last section.

One more remark may be in order here. All the conclusions we have reached about number of constituents are based on data on average multiplicities. Consequently, we can only say that on the average the number of constituents in hadron is equal to the number of quarks. To answer the problem of whether they are actually equal, it is necessary to analyze the multiplicity fluctuations which shall give information on dispersion of the distribution of number of constituents. No such investigation was carried out so far.

In the next section we shall consider the quark model in more detail and show that it gives many interesting predictions which may be tested in future experiments.

III. FURTHER CONSEQUENCES OF THE QUARK MODEL

A. Particle Production by Different Hadrons

Generalizing slightly the arguments of the preceding section and assuming that a wounded strange quark produces the same rapidity plateau as a wounded nonstrange quark[*]

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[*] This assumption is supported by the experimental observation[43] that particle multiplicity in Kp interactions is similar to that in πp interactions.

one arrives at the following predictions for A-dependence of particle production by different beams:

$$\begin{array}{ll}
\text{K beam} & R_A = \dfrac{\sigma_{QA}+\sigma_{SA}}{\sigma_{KA}} \\[2ex]
\phi & R_A = \dfrac{2\sigma_{QA}}{\sigma_{\phi A}} \\[2ex]
\Sigma \;\&\; \Lambda & R_A = \dfrac{2\sigma_{QA}+\sigma_{SA}}{\sigma_{\Lambda A}} \\[2ex]
\Xi & R_A = \dfrac{(\sigma_{QA}+2\sigma_{SA})}{\sigma_{\Xi A}}
\end{array} \tag{3.1}$$

where σ_{QA} and σ_{SA} are inelastic, non-diffractive cross-sections of non-strange and strange quarks. These predictions are plotted (together with those for proton and pion beams given in previous section) in Fig. 6 versus the so called "average number of collisions" ν_{hA} given by Eq. (2.6).

The inelastic cross-section of strange quark σ_{SH} was taken 4.5 mb [44] and generalization additivity rule (2.7) was used to calculate hadronic cross-sections from hydrogen. The nuclear inelastic cross-sections needed to calculate the number of wounded quarks were estimated from the Glauber model formula (2.6).

A characteristic feature seen in Fig. 6 is that the points cluster around the two well-separated lines, one for baryons and one for mesons. This again indicates that the only essential parameter is the number of constituents in the incident hadron. The measurements of particle production in central region by hyperon beams would be thus very useful for testing the ideas advocated here.

There is one particularly interesting case which is worth mentioning separately. If indeed the additivity rule works for Ξp cross-section, we expect $\sigma_{\Xi H} = \sigma_{QH} + 2\sigma_{SH} \simeq 19$mb. One notices that this is very close to the πp inelastic non-diffractive cross-section (∿20 mb). Thus we have two different projectiles with very similar cross-sections in hydrogen (and, consequently, also in nuclei). As seen from Fig. 6, however, the expected A-dependence of particle production is quite different in the two cases: the cascade baryon, having more constituents, should exhibit more A-dependence. This should be contrasted with predictions of the models which relate the A-dependence of particle production to the cross-section (or number of collisions) of the projectile.[18,22] Indeed, if the cross-section is the only relevant parameter, then A-dependence should be the same for Ξ and π beam. Thus the comparison of π and Ξ induced reactions in nuclei should provide a decisive test of the idea that the structure of the incident hadron is important for those phenomena. This observation is clearly much more general than a specific model we are exploring here.

B. Projectile Fragmentation Region

The results we were discussing until now are expected to be valid in the central region of rapidity. It is obviously quite important to analyze what happens outside of this region. Typical data showing projectile fragmentation region are shown in Fig. 7.[45]

Before further discussion, it is important to emphasize that, whereas the results for the central region depend essentially only on the number of hadronic constituents, the projectile fragmentation region is much more sensitive to the details of the mechanism of the hadron formation. This gives more ambiguity in the predictions but, at the same time, provides opportunity of testing different mechanisms of the transition from hadronic constituents to hadrons.

Basically, two different approaches were considered: (a) decay and/or recombination of spectator quarks and (b) collective fragmentation model.

Let me now discuss their characteristic predictions.

(a) Spectator Quark Fragmentation Model

It was noted by Anisovich, et al.[31] that the important source of secondaries in projectile fragmentation region may be the decay of spectator constituent quarks which did not take part in the interaction (did not get wounded, in our language). This is because those spectator quarks have a tendency to be faster than the wounded ones (They do not lose energy for emitting secondaries in the central rapidity region.). If this is indeed the case, one immediately concludes that the number of particles produced in the projectile fragmentation region should be decreasing with increasing A. This is illustrated in Fig. 8.

An estimate of such effects in Ref. 31 was shown to agree with the data at 20 & 24 GeV.[46] A similar model was recently discussed in Ref. 47 where many additional relations were derived and some of them compared successfully with the data.

If one assumes a specific model for spectator quark recombination functions, many predictions can be obtained. Nikolaev and collaborators[9,48] discussed this problem extensively using the quark recombination model[49] as a guideline.*

Actually, I feel that the situation in the fragmentation region is slightly more complicated than presented in Refs. 31, 47, 48. Since the quarks do not have fixed momentum, fast wounded quarks can contribute to particle production in the projectile fragmentation region, and one should consider both contributions.

For the incident mesons we can thus write simply

$$n_A(y) = w_A n_w(y) + (N_h - w_A) n_{sp}(y) \tag{3.2}$$

where $N_h - w_A$ is the number of quarks which did not get

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*Although most of the data was satisfactorily described by authors of Ref. 9,48, it seems that the new data of Ref. 50 give an evidence against the recombination model, as used by them. As noted by Nikolaev, et al.,[9,48] according to the recombination model, there should be a dramatic difference between the A-dependence of spectra for secondary particles which do have common quarks with the incident one and those which do not have common quarks; since the latter cannot be produced by recombination of spectator quarks, they should have always $R_A \geq 1$, i.e., their production should increase with increasing A. This prediction is strongly violated by data of Ref. 50 which shows identical A-dependence for Λ and $\bar{\Lambda}$ production (both having $R_A < 1$ for $x > .2$). Let me emphasize that the data of Ref. 50 do not contradict the general quark model formula, but only a simple recombination model for $n_{sp}(y)$ used in Refs. 9 and 48.

wounded and $\bar{n}_{sp}(y)$ is the multiplicity of secondaries produced by one such a spectator quark* Since w_A increased with A and $n_{sp}(y)$ is independent of A, this term must decrease with A. This is shown in Fig. 9.[51]

On the other hand, the first term in the R.H.S. of Eq. (3.2) increases with A, provided that, as we always assume, $n_w(y)$ is independent of A.[27,28] Since we do not know the exact form of $n_w(y)$ and $n_{sp}(y)$, it is not possible to predict exactly the A-dependence of the spectrum. However, it is interesting to observe that the Eq. (3.2) implies that the particle density is a linear function of the average number of wounded quarks:

$$n_A(y) = N_h\ n_{sp}(y) + w_A\Big(n_w(y) - n_{sp}(y)\Big) \ . \qquad (3.4)$$

Thus the spectator quark model suggests a very specific parametrization of A-dependence. It would be interesting to test this parametrization and use it for determining quark decay functions $n_w(y)$ and $n_{sp}(y)$.[51]

The formula (3.2) has many consequences for quantum numbers of the observed final particles. This is because the A-dependence of the spectra shall reflect $n_w(y)$ and $n_{sp}(y)$ which are expected to be different for different quarks and different detected particles. This should not affect the predictions of the model in the central rapidity region,

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*For incident baryons the formula becomes more complicated, because it is necessary to account for the probability that two spectator quarks recombine to make one final baryon.[31,47] For more detailed discussion, see Ref. 51.

which is dominated by $n_w(y)$ and thus insensitive to quantum numbers of final particles. However, as we move towards the projectile fragmentation region the interesting effects may appear. The exact predictions depend on the form of the quark fragmentation functions $n_w(y)$ and $n_{sp}(y)$, and are therefore ambiguous. I would rather advocate using the experimental data in order to extract the quark decay functions and try to understand their systematics.[51]

(b) Collective Fragmentation Model

It is by no means obvious that the quarks contribute independently to the particle production in the projectile fragmentation region, as assumed in the spectator quark model. One may actually argue that, since they happen to be very close in phase-space, they may interact strongly before changing into hadrons, and therefore one cannot neglect the collective phenomena.[*] Such a point of view seems less attractive than the one advocated in Ref. 31, because it does not give so many specific predictions, at least as long as we cannot calculate these collective effects. It is, nevertheless, interesting to try to estimate what are the expectations from such a collective fragmentation model, in order to contrast them to the other one. This problem was discussed in Ref. 29.

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[*] A simple example of the model which may lead to such a picture is the Low model of high-energy interaction of hadron bags.[52] In this model contribution to the projectile fragmentation region comes from the decay of the whole hadron bag and is not necessarily a sum of contributions from the individual quarks.

Since nothing is known about the collective phenomena in the fragmentation of the fast hadron, the authors of Ref. 29 took the extreme point of view, namely that in the fragmentation region all the memory of the quark structure is lost and the distribution of final particles is just governed by (longitudinal) phase space. Such a simplified approach can be motivated by the well-known fact that the observed spectra in hadron-hadron collisions are, to a large extent, determined by energy and momentum conservation laws.[53] In particular, the simple longitudinal phase-space (including cluster production and leading particles[54,55]) seems to be a very good description of bulk of hadronic production at small transverse momenta.

It was shown in Ref. 29 that, although the phase-space does not influence significantly the A-dependence of the spectra in the central region, it does modify it strongly in the fragmentation region of the projectile. As a matter of fact, the phase-space itself can explain a large part of the decrease of spectra with increasing A at high rapidities (see Fig. 7).

Qualitatively, it is rather straightforward to see that if the spectrum increases with increasing A in the central region, it must decrease in projectile fragmentation region.[56] Simply, since there are more particles produced in the central region, there is not enough energy left to produce very fast particles and the fragmentation decreases. A typical result of the phase-space calculation[29] for A-dependence of the spectrum is shown in Fig. 10 for 300 GeV incident neutrons, together with data of Ref. 45. It is seen that there is only very little modification in the central region at this energy. It is also seen that the phase-space prediction follows the data quite closely in the projectile fragmentation region. This indicates that the fragmentation region is fairly well described by kinematic effects, provided the central region density is correctly chosen. It follows that it may not be easy to disentangle different mechanisms of particle production in this region, without detailed investigation of the quantum number correlations (the phase-space corrections are sensitive only to the masses of the produced particles and not to other quantum numbers).[29*]

C. Comparison With Other Models

Let me close this section with a few remarks about comparison of the quark model with some other models of particle production from nuclei.

a. The eikonal model predicts that for every projectile h

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[*] This observation leads to a striking prediction that A-dependence of the spectra should be the same for particles and antiparticles. It is actually quite well confirmed by data for Λ and $\bar{\Lambda}$. I would like to thank K. Doroba for pointing out this data to me.

$$R_A = f(A)\ \nu_{hA}, \tag{3.5}$$

where f(A) is universal function of A, which does not depend on projectile h[18]. Although the Eq.(3.5) looks similar to our Eq.(2.5), it should be noted that their consequences are quite different. In Eq.(2.5) the coefficient $1/\nu_{cA}$ which multiplies ν_{hA} does depend on the nature of the projectile h (because the quark content may be different for different projectiles). This is an important point because, if Eq.(3.5) is applied to projectiles with very small cross sections on nucleons (e.g. heavy vector mesons), it implies* $f(A) \simeq 1$. Since f(A) does not depend on projectiles we recover the well-known result of the standard eikonal model

$$R_A = \nu_A, \tag{3.6}$$

which is in clear contradiction with the data, as seen e.g. in Fig. 3.

b. The model of Ref.24 expresses R_A as an integral over parton energy distribution. The authors calculated R_A for 200 GeV incident protons. It is plotted in Fig. 11, together with our calculation (Eq.2.5) for comparison. One sees that the results are close and differ substantially

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*The condition $\sigma_{hH} \to 0$ implies $\nu_{hA} \to 1$, independently of A.

only at large A. At higher energies the model of Ref. 24 predicts further increase of R_A, so that the difference is expected to grow. The data at present[5] cannot clearly distinguish the two models, although the quark model seems slightly favored.

c. The model of Ref. 22 gives a simple formula for R_A.

$$R_A(y) = \bar{\nu}_{hA}(\tfrac{1}{2} - \tfrac{y}{Y}) + \{1 - (\tfrac{1}{2} - \tfrac{y}{Y})\bar{\nu}_{hA}\} \qquad (3.7)$$

where y is the cm. rapidity, and Y is the length of the central region at a given energy. To compare with the data, we integrated the formula (3.7) for $3 \leq y_{lab} \leq 4$ at 200 GeV incident momentum ($y_{lab} \simeq 3 + y_{cm}$). The results are sensitive to the choice of Y. In order to obtain agreement with the data Y has to be chosen $\lesssim 3$, which seems to be a little low, since the full length of the rapidity interval for pions at this energy exceeds 8 units. The results for $Y=3$ are plotted in Fig. 11.

D. Modified Cascade Model[25]

Finally, the results of the modified cascade model of Ref. 25 are plotted in Fig. 11. It is seen that they agree very well with the data of Ref. 5.

My general impression is that there is still much work to be done before one will be able to decide finally which model is the right one. At present the high energy data are rather scarce and no comprehensive critical comparison with models was done. For more detailed discussion of different models, the reader is referred to Ref. 9.

IV. NUCLEUS-NUCLEUS INTERACTIONS

A. Central Rapidity Region

A good part of the argument of the previous sections can be generalized to include the nucleus-nucleus collisions.

Consider first the central rapidity region.[28] Let nucleus A be incident at high energy on a target. We first calculate the ratio $n_{AB}(y)/n_{AH}(y)$ of multiplicities when targets are nucleus B and hydrogen. According to the model of Ref. 28, this ratio is equal to the ratio of the number of wounded quarks in A for those two cases. Thus we have

$$\frac{n_{AB}(y)}{n_A(y)} = \frac{W_{AB}}{W_A} = \frac{N_A\sigma_{qB}}{\sigma_{AB}} : \frac{N_A\sigma_q}{\sigma_A} = \frac{\sigma_A\sigma_{qB}}{\sigma_{AB}\sigma_q} \tag{4.1}$$

where N_A is the total number of quarks in nucleus A; σ_q and σ_A are quark-nucleon and A-nucleon inelastic nondiffractive cross-sections. Using now Eq. (2.5) we obtain for the ratio $R_{AB}(y)$

$$R_{AB}^{\text{central}}(y) \equiv \frac{n_{AB}(y)}{n_{HH}(y)} = \frac{\sigma_H\sigma_{qA}\sigma_{qB}}{\sigma_{AB}\sigma_q{}^2} = \frac{\nu_{AB}}{\nu_{qA}\nu_{qB}} \tag{4.2}$$

there ν_{AB} is the total number of inelastic nucleon-nucleon collisions in A+B scattering

$$\nu_{AB} = \frac{AB\ \sigma_H}{\sigma_{AB}} \tag{4.3}$$

and ν_{qA}, ν_{qB} are number of collisions of quarks in A and B, given by Eq. (2.6). The numerical estimates of Eq. (4.2) are shown in Fig. 12 for different beams and target nuclei. It is seen that the results depend mainly on the product A,B. The most amazing feature seen in Fig. 12 are the large values of multiplicities which can be obtained in scattering of heavy nuclei. This indicates that the extrapolation one makes from nucleon-nucleus to nucleus-nucleus case is rather considerable. It would be indeed surprising if it would survive precise experimental tests.

Equation (4.2) was found to be compatible with cosmic ray data.[29] For comparison also the prediction from the model of Ref. 22 is plotted in Fig. 12. It is seen that the two models differ substantially only for collision of two very heavy nuclei.

The formula (4.2) is a generalization of Eq. (2.5) for nucleus-nucleus collisions. As Eq. (2.5), Eq. (4.2) is also expected to be valid in the central region of rapidity. This may mean very high energies, because at low energies the plateau is simply not present.

It is therefore of importance to analyze the projectile fragmentation region which most probably dominates the data at present energies. Unfortunately, this involves understanding of the processes of nuclear fragmentation and intra-nuclear cascading of slow secondaries (in nucleus rest frame), and thus appears to be fairly complicated.

No detailed discussion of this problem exists, therefore I shall restrict myself to few remarks.

B. Target Fragmentation Region

Consider first a special case of target fragmentation region in nucleon-nucleus collisions. A simple picture of multiple scattering inside nucleus suggests that multiplicity in this region should be approximately ν_{hA} times that in hydrogen. The possible cascading phenomena and Fermi motion effects[57] modify this simple prediction, but hopefully only in close neighborhood of the phase space limit. Indeed, in the region $y \lesssim 0 \lesssim 2$ the formula

$$n_A = \nu_{hA} n_H \tag{4.4}$$

works quite well,[5,38,58] supporting the picture of target nucleons interacting independently with the projectile.

If we follow the picture of the spectator fragmentation model, as described in the previous section, the general formula for multiplicity distribution in hadron-nucleus collisions should be written as*

$$n_A(y) = 2\nu_{hA} n_{sp}^{(-)}(y) + w_A n_w(y) + (3-w_A) n_{sp}^{(+)}(y) \tag{4.5}$$

where $n_{sp}^{(-)}(y)$ is the contribution from a spectator quark in the target and $n_{sp}^{(+)}$ is the contribution from a spectator quark in the beam. $n_w(y)$ is the contribution from wounded quarks. For y in the fragmentation region of the target this contribution is probably depending on A (proportional to ν_{qA}), so that the formula (4.4) is recovered in this region.

---

*To simplify our semi-quantitative discussion, we neglect the difference between decay of spectator quarks and diquarks. A more general formula can easily be written down.[51]

It should be stressed again that Eq. (4.5) probably underestimates the multiplicity in target fragmentation region, where cascading is expected to occur and where the data do indeed show multiplicity rising faster than ν_{hA}.[5] It is not clear to me at the moment what shall be the consequences of the internal motion inside the nucleus, but this effect can probably be estimated.[57]

We may ask now what is the proper generalization of the formula (4.5) for the target fragmentation in nucleus-nucleus collisions. As far as I can see, the most likely possibility is that multiplicity is proportional to the number of spectator quarks in wounded mucleons in the target. Thus we obtain for collision B + A

$$n_{AB}(y) = W_A{}^N(3-w_B)n_{sp}^{(-)}(y) + R_{AB}^{central} n_W(y) + \\ + W_B{}^N(3-w_A)n_{sp}^{(+)}(y) \qquad (4.6)$$

where $W_A{}^N$ and $W_B{}^N$ are numbers of wounded nucleons in A and B, respectively and $R_{AB}^{central}$ is given by Eq. (4.2). $n_{sp}^{(-)}$ is the contribution from a spectator quark in the target (A) and $n_{sp}^{(+)}$ that is beam (B) nucleus. Again, it should be pointed out that $n_W(y)$ may depend on A and B in the fragmentation regions, so no easy predictions are possible in general. Also the remarks about cascading phenomena and internal nuclear motion which I made before apply here as well.

With all of these caveats in mind, it is still interesting to see how the contribution from fragmentation region compares with that of central region, given by Eq. (4.2). Neglecting the central region we obtain

$$n_{AB}(y) = W_A{}^N(3-W_B)n_{sp}^{(-)}(y) + W_B{}^N(3-W_A)n_{sp}^{(+)}(y) \qquad (4.7)$$

If we assume that $n_{sp}^{(+)}(y)$ gives contribution only to forward hemisphere and $n_{sp}^{(-)}(y)$ only in backward hemisphere we obtain for integrated multiplicities

$$n_{AB} = \tfrac{1}{2}\{W_A{}^N(3-W_B) + W_B{}^N(3-W_A)\}n_H \qquad (4.8)$$

where n_H is multiplicity in proton-proton collision. The first term comes from the target (A) hemisphere and the second term from the beam (B) hemisphere. The ratio $R_{AB} \equiv n_{AB}/n_H$ obtained from Eq. (4.8) is plotted in Fig. 13. One sees that the obtained multiplicities are substantially lower than the ones from Eq. (4.2) Fig. 12 . Thus, one expects ratio R_{AB} to increase with increasing energy, as the central region becomes more and more important.

V. OUTLOOK

I tried to argue in this talk that the constituent quark model provides a successful phenomenology of hadron-nucleus collisions at low momentum transfers. The natural next question is if this success can be understood in terms of a more fundamental theory. I shall close my lecture by some spectulations on this subject.

First let me emphasize again an important ingredient in our treatment of the quark model[27,28]: to obtain agreement with data it was necessary to assume that, in the central region of rapidity, radiation of particles from a "wounded" quark is independent of the target, i.e., of the number of scatterings it suffered from the target. This assumption looks fairly natural in the laboratory frame, where quark is fast and nucleus is at rest. Consider, however, the situation in the rest frame of the projectile.[28] In this frame, nucleus is bombarding the hadron with large energy and now quarks in the nucleus radiate final particles. If we like to be consistent we have to assume that total radiation from all quarks in the projectile nucleus which interacted with just one given quark in the hadron target is the same as from one quark. This is so because amount of radiation in the central region obviously cannot depend on the frame of reference we are choosing. When stated that way, this phenomenon is clearly much more difficult to understand. One possibility of understanding it is to notice that in the anti-laboratory frame the nucleus shrinks because of Lorentz contraction. Consequently, all constituent quarks which have the same impact parameter actually cannot be distinguished and behave as a single quark. The consequences of this effect were first described by Kanchelli[15], who argued that in such a case radiation is independent of the size of the target

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*Kanchelli applied this argument to hadrons (not to quarks) and consequently obtained $R_A=1$ in the central region.

Another possibility, perhaps more attractive, is to observe that a similar phenomenon occurs if particle production at high energy is described by exchange of color gluons between colored quarks as suggested by Low.[52] In the Low model particle production occurs long after the exchange of gluons takes place and is caused by necessity to rearrange color in the final state so that two color octet states which move with high velocity in opposite directions do not show up as real particles. This amounts to breaking of the colored gluon "string" which connects the two octets (Fig. 14). The multiplicity of hadrons created in this way is likely to depend only on the amount of color in the "string", at least in the central region, not too close to the ends of the string. Now, the important point to observe is that in scattering from a single quark only two color exchanges are possible, independently of the number of scatterings: singlet and octet. Singlet exchange leads to diffractive interactions which we are not discussing here. This leaves us with unique possibility of octet exchange. Consequently, we indeed expect the same multiplicity created by one quark, independently of the number of times it scatters.

This argument requires the assumption that, if the two color strings are close to each other, they shall interact and collapse into one.[*] This seems to me a reasonable hypothesis

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[*] The necessity of such self-interaction between "sparks" was already recognized in Ref. 27.

because the energy of one string is clearly smaller than two separate strings with the same color content.* Finally, let me add that in this picture the actual calculations may be quite involved, because the radiation must also depend on the (transverse) distance of the quarks inside the hadron (if the transverse distance between wounded quarks in the projectile is smaller than the range of interaction of the color tubes, those two quarks shall be seen as one object with (possibly) more complicated color content).

Although the picture presented here looks fairly natural in a theory of colored quarks and gluons, it should be realized that it indicates just the possibility and not yet a developed model. The main point (apart from obvious difficulties of applying QCD for low q^2 processes) is that in the Low model it is not trivial to calculate the number of wounded quarks: the model is formulated with amplitudes rather than probabilities—strong interferences between the amplitudes expected in small q^2 region destroy the naive probabilistic interpretation.† Thus more work should still be done on this problem before final conclusions are reached. I feel however that this is a very attractive possibility of understanding high-energy nuclear scattering and relating it to the fundamental theory of strong interactions.

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*Other possibility was discussed by S. Brodsky at this meeting.

†I would like to thank Professor F. Low for an illuminating discussion about this point.

In conclusion, let me emphasize that, although the quark model of hadron nucleus interactions at high energies is far from being proven by existing experiments, it definitely provides an attractive possibility of interpretation of the data: (i) it gives many simple predictions, (ii) it allows the extraction from data of some interesting information about hadronic constituents and finally (iii) it gives a hope to relate the hadron-nucleus interactions to fundamental theory of hadrons. I feel that it is indeed worthwhile to undertake further investigations in this direction.

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FIGURE CAPTIONS

Fig. 1 Low momentum transfer hadron-hadron collision.

Fig. 2 Low momentum transfer hadron-nucleus collision.

Fig. 3 Interaction of hadronic constituents in hydrogen and in nucleus.

Fig. 4 R_A from Eq. (2.3) plotted versus average number of collision ν_p of protons in nuclear data from Ref. 5. $\sigma_{pp} = 30$ mb.

Fig. 5 R_A from Eq. (2.3) plotter versus average number of collisions ν_π of pions in nuclear target. Data from Ref. 38. $\sigma_{\pi p} = 20$ mb.

Fig. 6 R_A for different projectiles calculated from Eqs. (2.3) and (3.1), plotted versus average number of collisions ν_h.

Fig. 7 Data from Ref. 45 showing A dependence of negative particle spectrum in the forward hemisphere for 300 GeV neutron-nucleus interactions. Line is the result of Eq. (2.3).

Fig. 8 Spectator quark contributions to the projectile fragmentation region.

Fig. 9 A-dependence of the spectator quarks contribution to particle production for pion and nucleon beam plotted versus atomic number of the target.

Fig. 10 Longitudinal phase space calculation[29] of the A-dependence of negatives spectrum for 300 GeV neutron-nucleus collisions. Data from Ref. 45.

Fig. 11 Comparison of different models of particle production. Data from Ref. 38.

Fig. 12 Central plateau density in nucleus-nucleus collisions at high energy, $\sigma_{pp} = 32.3$ mb.[5] Closed symbols—results from quark model, calculated from eq. (4.2), Ref. 28. For comparison also results from Ref. 22 are shown.

Fig. 13 Fragmentation density in nucleus-nucleus collisions at high energy, calculated from Eq. (4.8). $\sigma_{pp} = 32.3$ mb.[5]

Fig. 14 Particle production in high-energy interactions, according to model of Ref. 52.

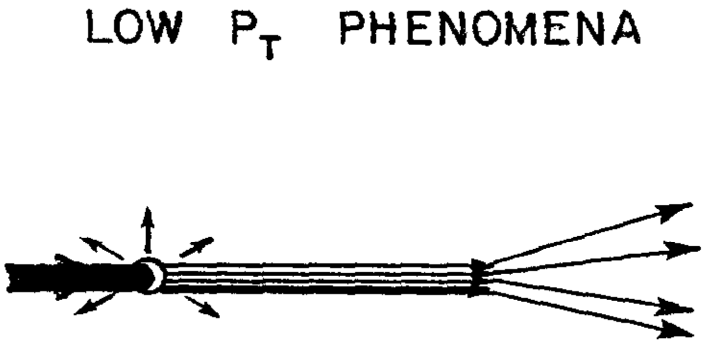
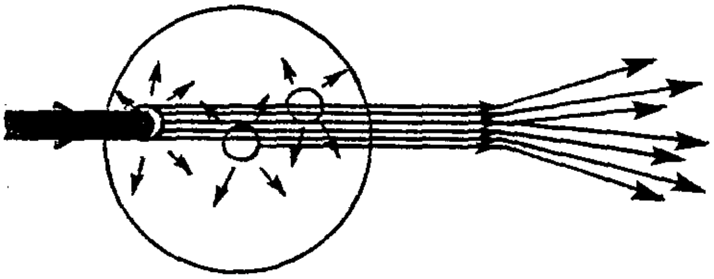


Fig. 1

NUCLEUS AS DETECTOR OF HADRONIC CONSTITUENTS

TIME RESOLUTION: 10^{-17} μsec

LOW P_T PHENOMENA



COLLECTIVE PARTON EFFECTS

Fig. 2

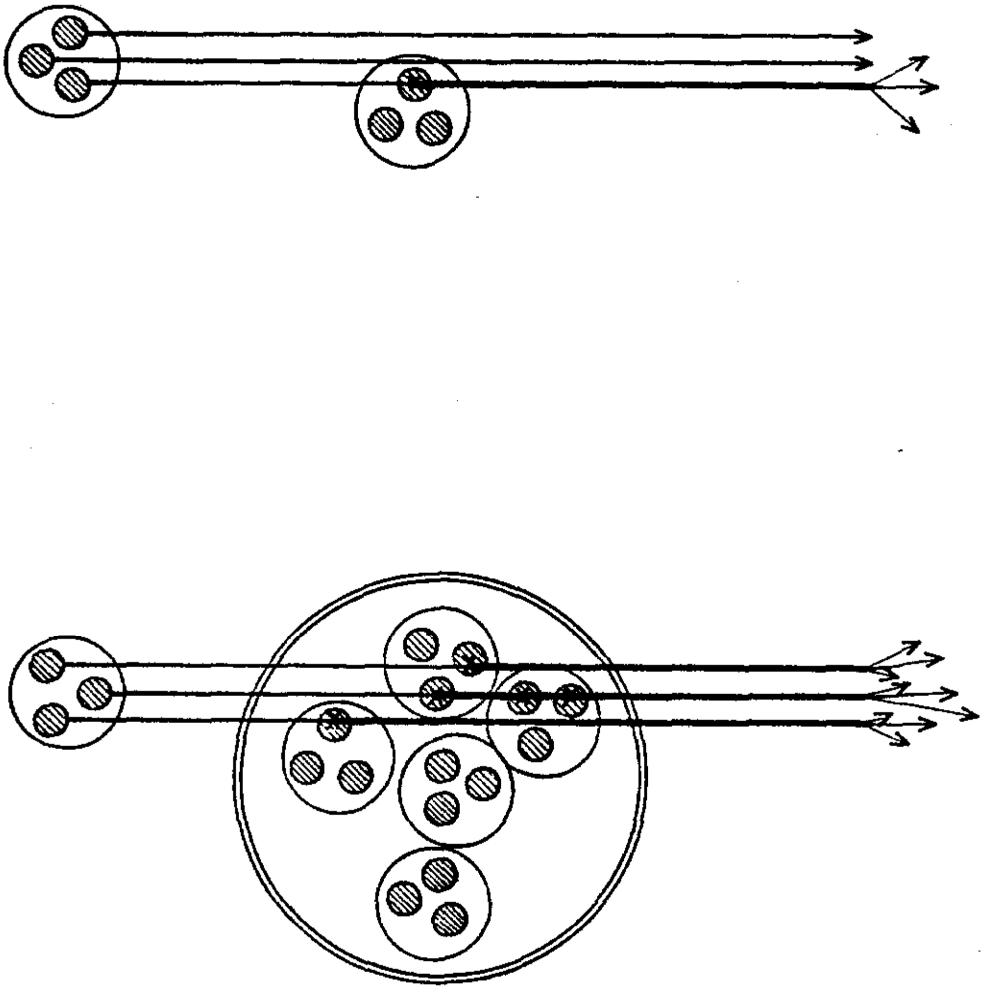


Fig. 3

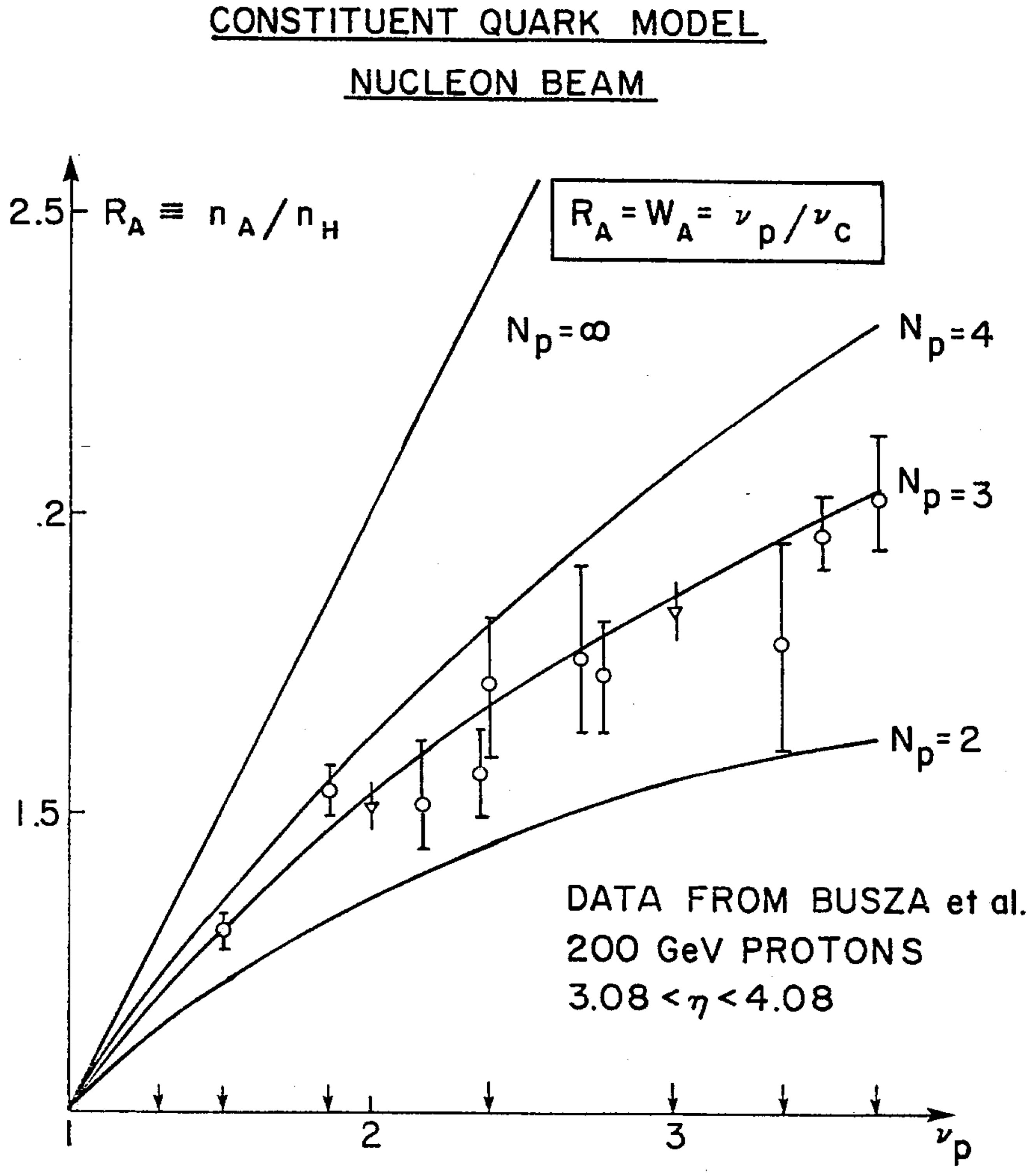

CONSTITUENT QUARK MODEL
NUCLEON BEAM
$R_A \equiv n_A / n_H$
$R_A = W_A = \nu_p / \nu_c$
$N_p = \infty$
$N_p = 4$
$N_p = 3$
$N_p = 2$
2.5
2
1.5
1
2
3
ν_p
DATA FROM BUSZA et al.
200 GeV PROTONS
$3.08 < \eta < 4.08$

Fig. 4

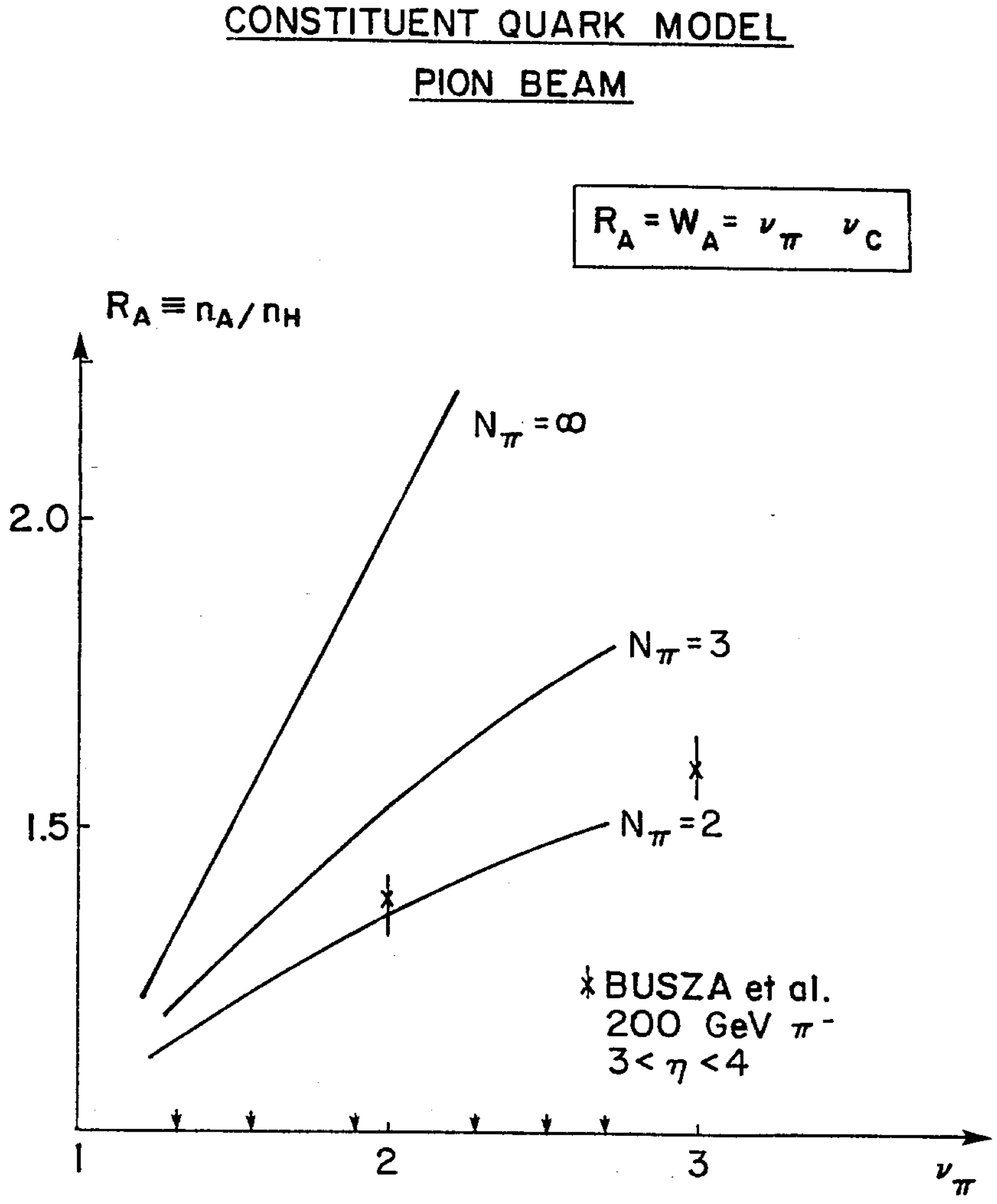

CONSTITUENT QUARK MODEL
PION BEAM
$R_A = W_A = \nu_\pi \quad \nu_C$
$R_A \equiv n_A / n_H$
2.0
1.5
$N_\pi = \infty$
$N_\pi = 3$
$N_\pi = 2$
BUSZA et al.
200 GeV π^-
$3 < \eta < 4$
1
2
3
ν_π

Fig. 5

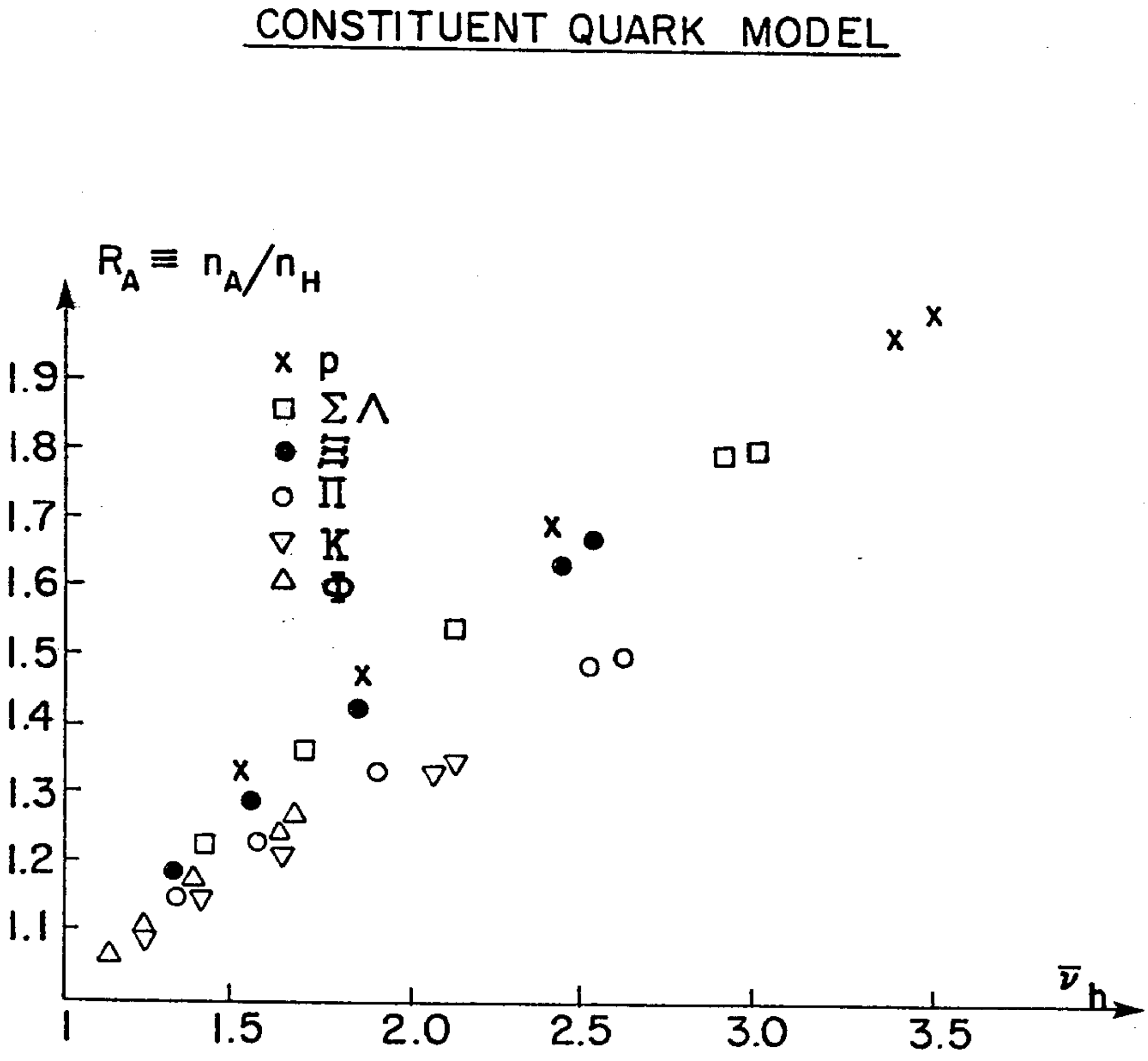

CONSTITUENT QUARK MODEL
$R_A \equiv n_A/n_H$
x p
□ Σ Λ
● Ξ
○ Π
▽ K
△ Φ
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
$\bar{\nu}_h$
1
1.5
2.0
2.5
3.0
3.5

Fig. 6

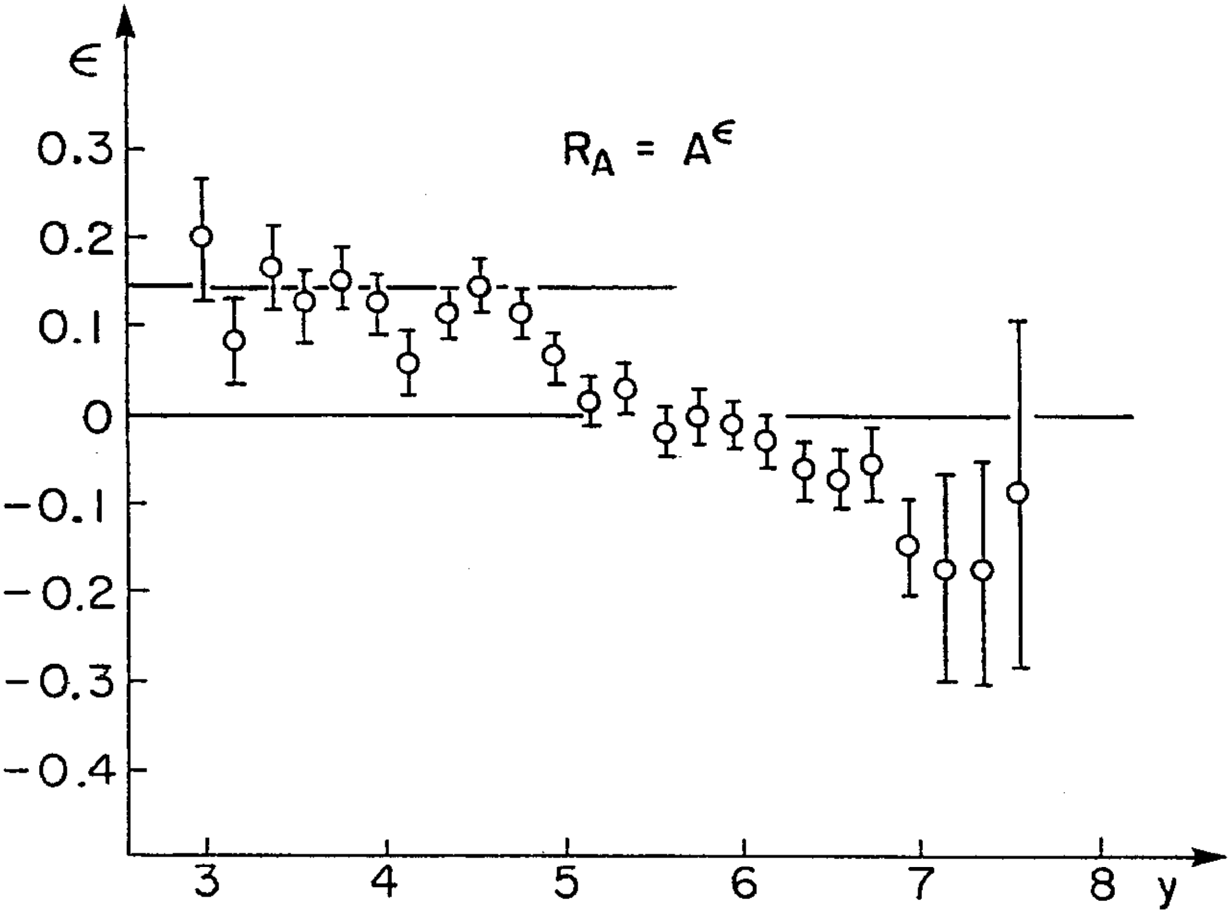


Fig. 7

PROJECTILE FRAGMENTATION REGION

ANISOVICH, SHABELSKY AND SHEKHTER N.P.B133 (1977)

N. NIKOLAEV, P.L. 70B (1977) 95.

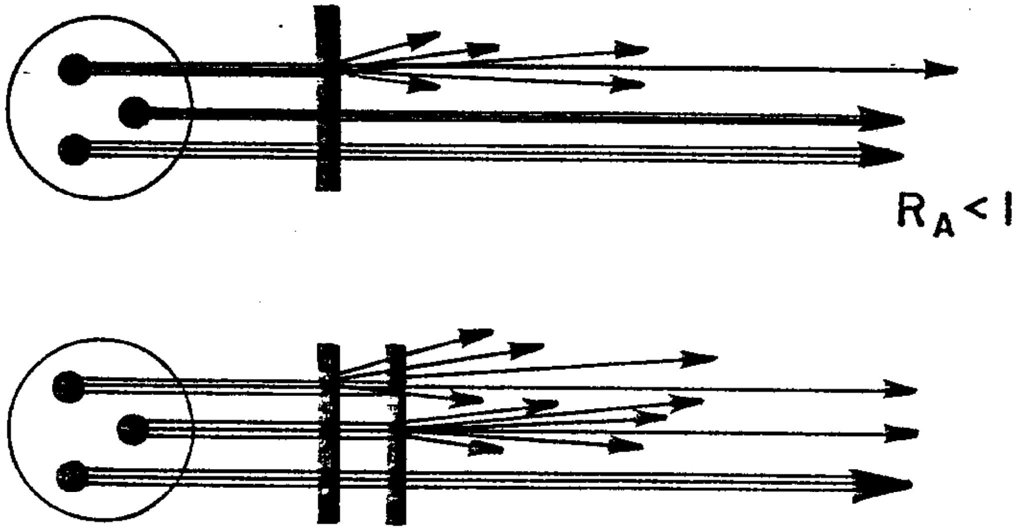


Fig. 8

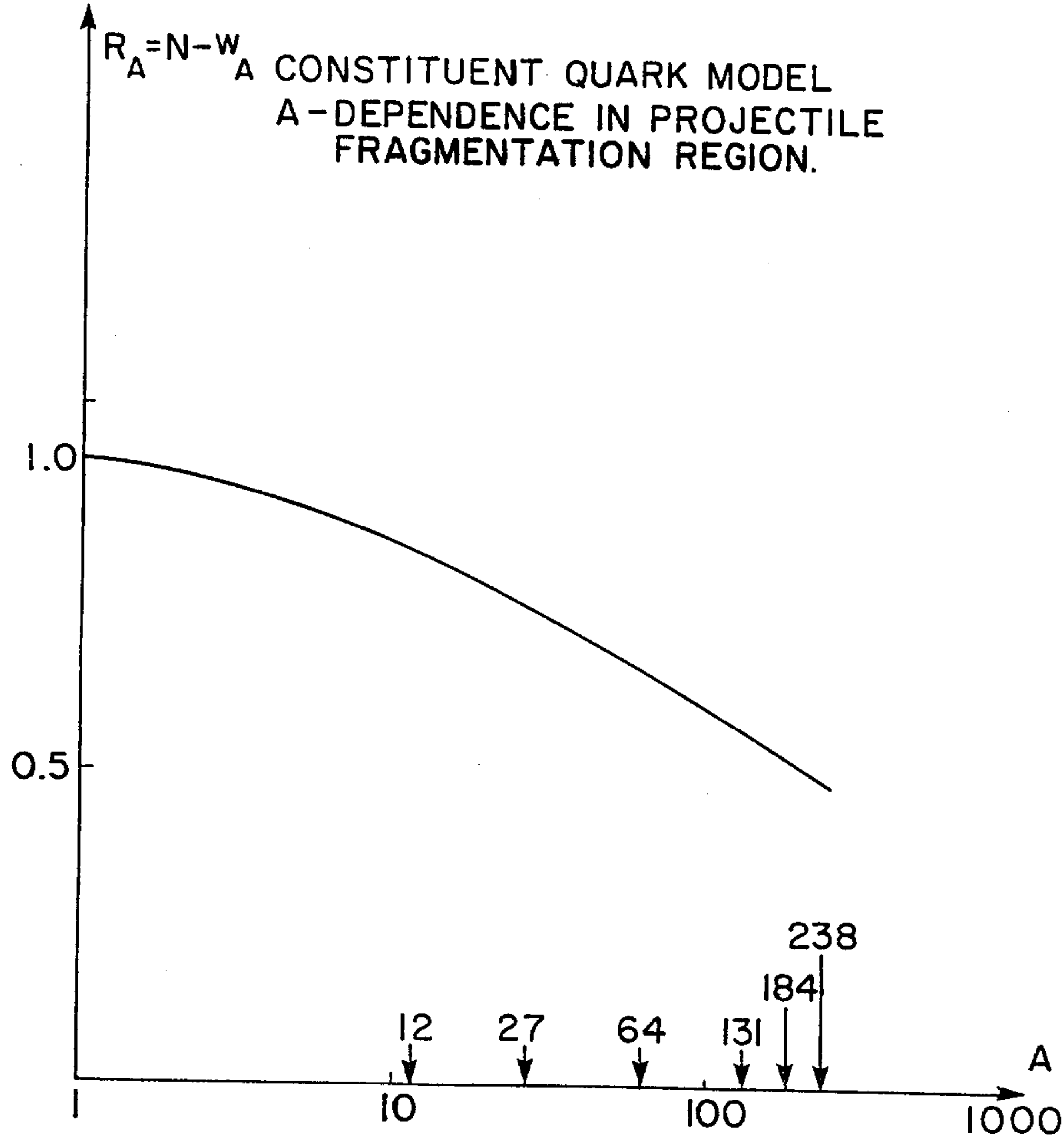

$R_A = N^{-w_A}$ CONSTITUENT QUARK MODEL
A-DEPENDENCE IN PROJECTILE FRAGMENTATION REGION.
1.0
0.5
12
27
64
131
184
238
A
1
10
100
1000

Fig. 9

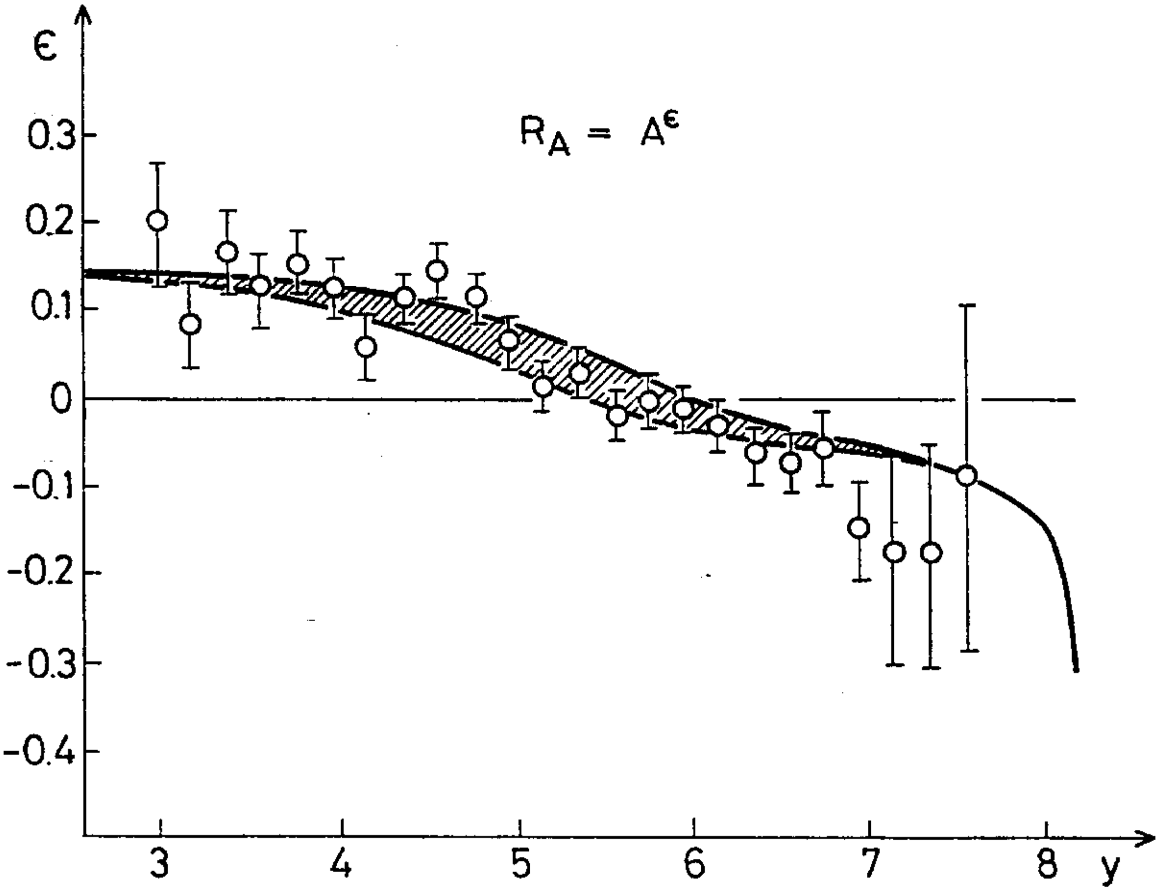
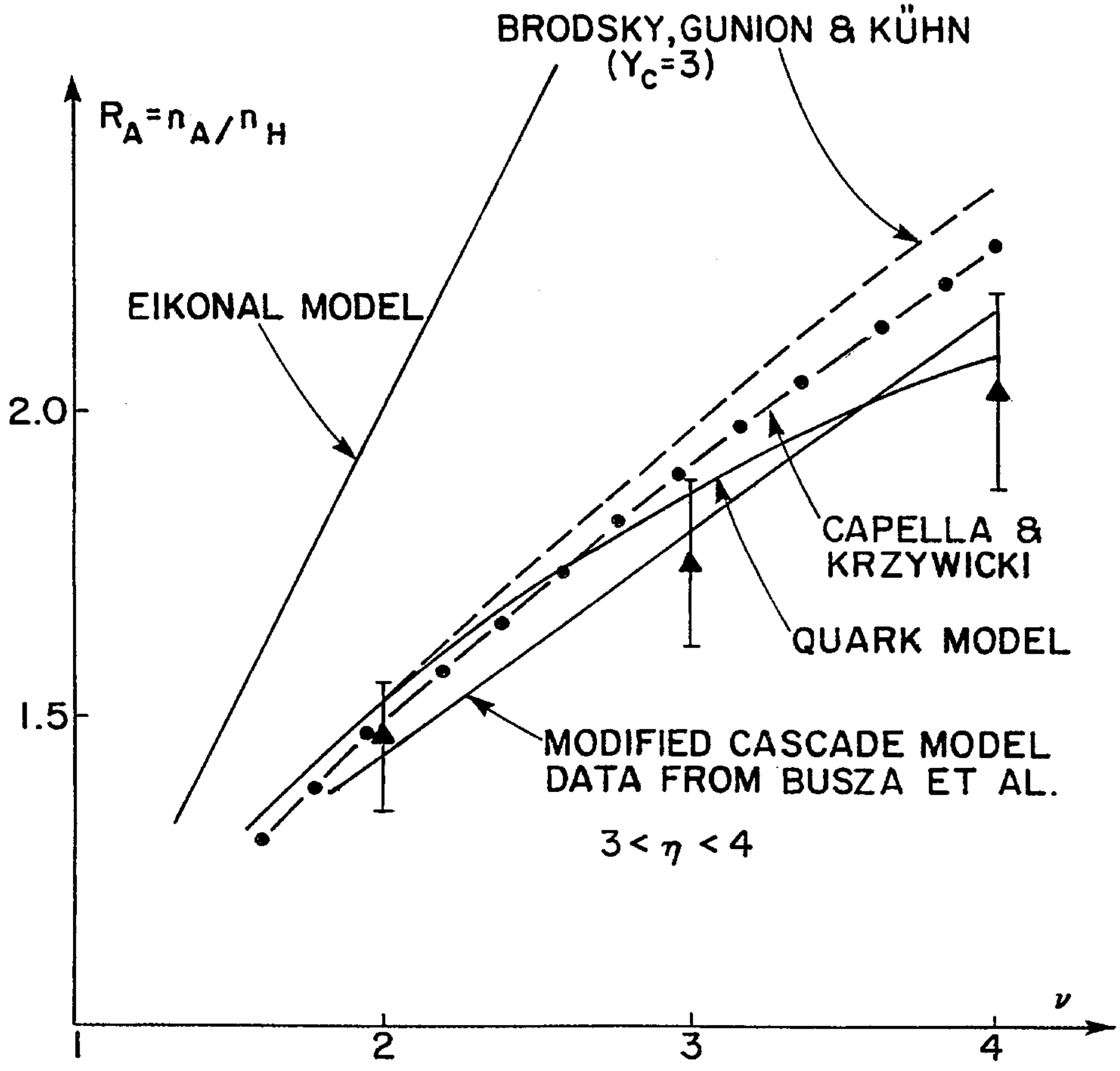


Fig. 10



BRODSKY, GUNION & KÜHN
($Y_C=3$)
$R_A = n_A / n_H$
EIKONAL MODEL
2.0
1.5
CAPELLA &
KRZYWICKI
QUARK MODEL
MODIFIED CASCADE MODEL
DATA FROM BUSZA ET AL.
$3 < \eta < 4$
ν
1
2
3
4

Fig. 11

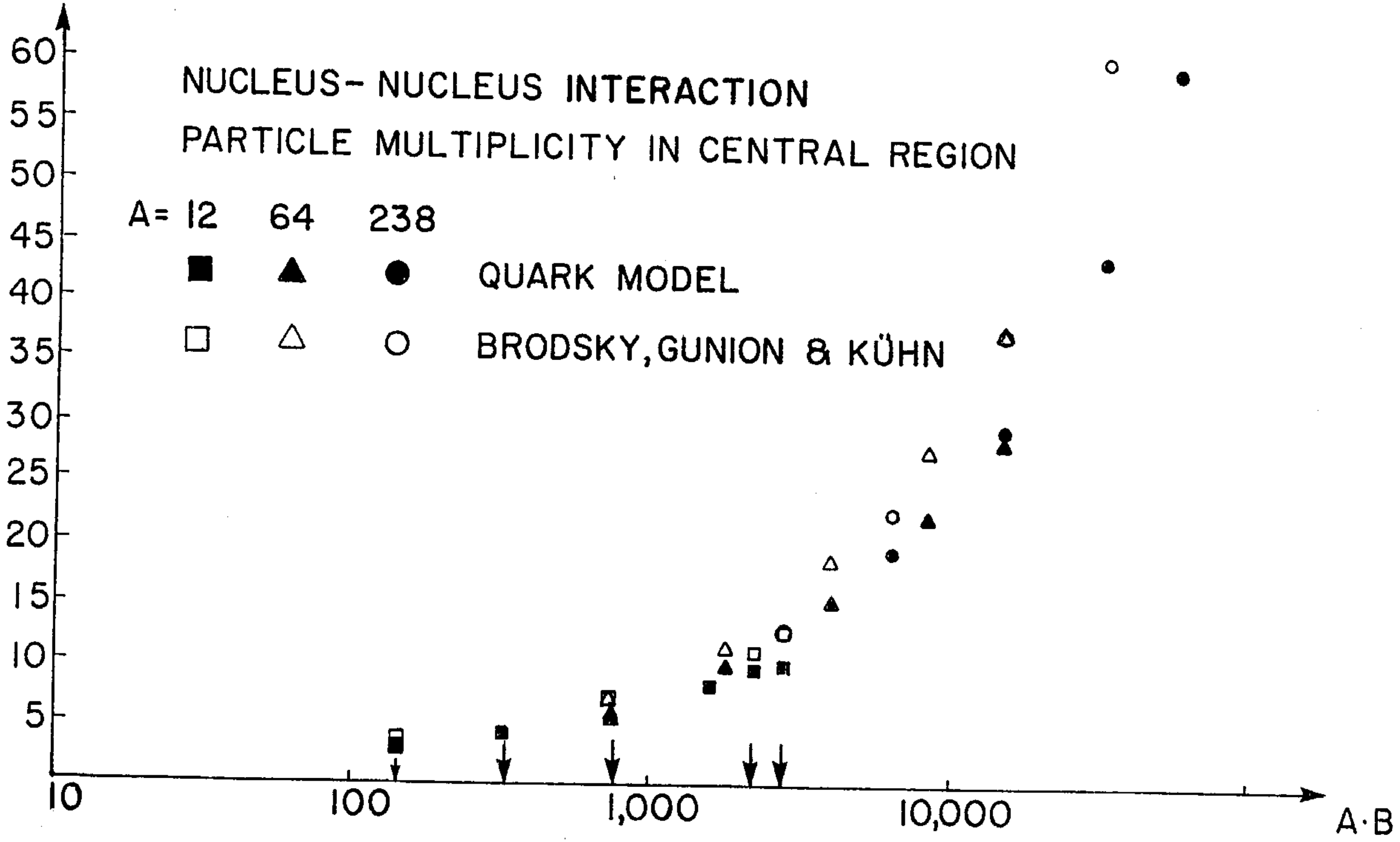

NUCLEUS- NUCLEUS INTERACTION
PARTICLE MULTIPLICITY IN CENTRAL REGION
A= 12 64 238
■ ▲ ● QUARK MODEL
□ △ ○ BRODSKY, GUNION & KÜHN
60
55
50
45
40
35
30
25
20
15
10
5
10
100
1,000
10,000
A·B

Fig. 12

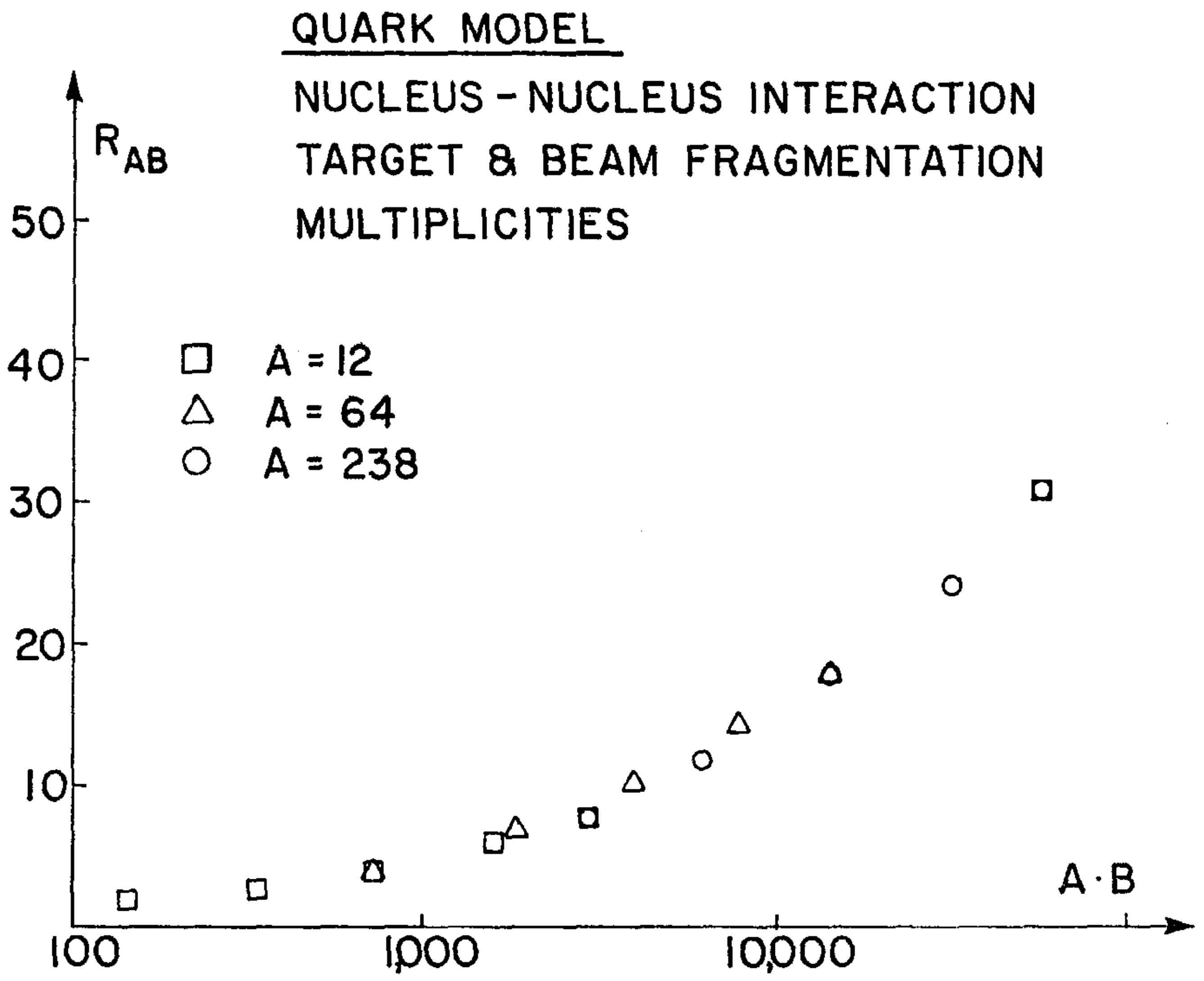
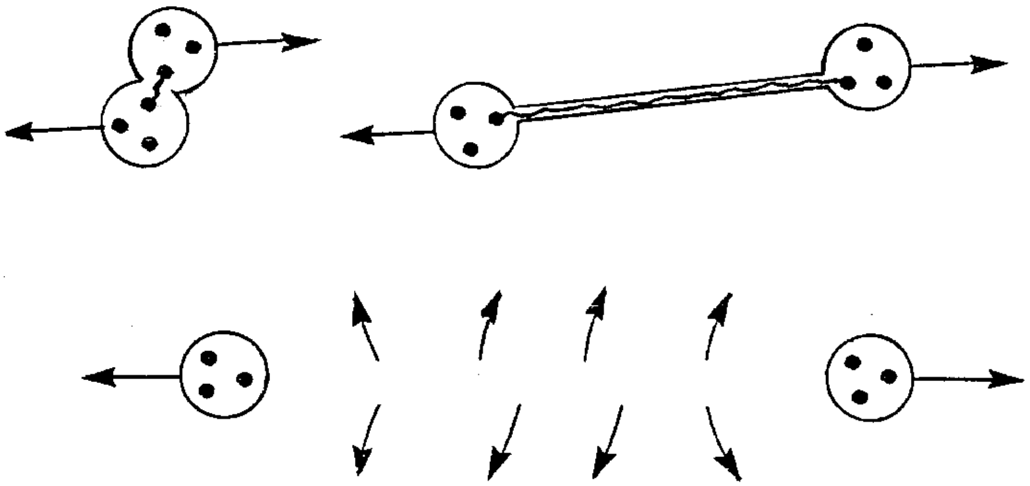

QUARK MODEL
NUCLEUS - NUCLEUS INTERACTION
TARGET & BEAM FRAGMENTATION
MULTIPLICITIES
R_{AB}
50
40
30
20
10
□ A = 12
△ A = 64
○ A = 238
A·B
100
1,000
10,000

Fig. 13

QUARK- QUARK INTERACTION BY EXCHANGE OF COLOUR GLUONS

(a) PROTON - PROTON INTERACTION



(b) PROTON - NUCLEUS INTERACTION

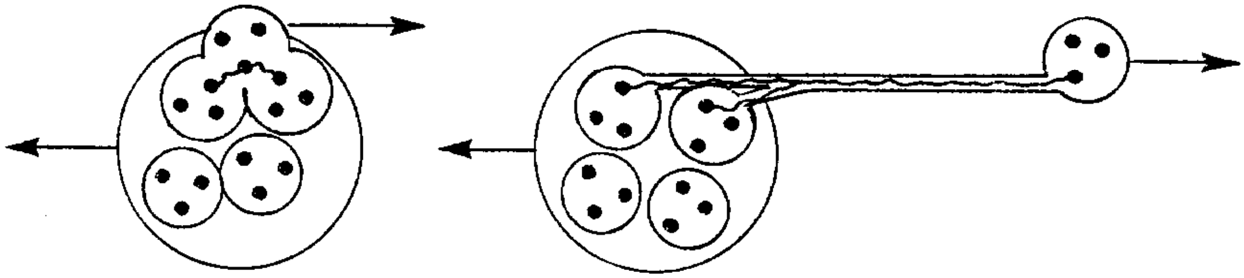


Fig. 14