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A MODEL FOR INCLUSIVE PRODUCTION FROM HIGH-ENERGY HADRON-NUCLEUS INTERACTIONS *

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It is shown that all aspects of the data on inclusive single-particle production from nuclei can be understood in terms of a model in which the interaction with the nucleus occurs through one or more elastic q-q scatterings. Successive scatters are assumed to be mostly incoherent. No cascading occurs because "dressing" of the scattered quarks does not take place until after the quarks leave the nucleus.

1. Introduction **

There are now considerable experimental data on inclusive particle production by very high energy hadrons incident on nuclei [2]. Briefly summarizing the data we can describe the results as follows:

(i) For forward angles (≲ 90° in the hadron-nucleon c.m.s., referred to as the projectile-fragmentation region), momentum and angular distributions from hadron-nucleon collisions are very similar to those from hadron-nucleus collisions with cross sections scaled by $\sigma_{\text{in}}(\text{h}A)/\sigma_{\text{in}}(\text{hN})$, the ratio of the hadron-nucleus inelastic cross section to that for hadrons on nucleons. The forward multiplicities per interaction are almost identical for nuclear and nucleon targets [2a].

(ii) For larger angles (≳ 90° in the h-N c.m.s., referred to as the target-fragmentation region) multiplicities per interaction grow roughly as the nuclear radius or $\propto A^{1/3}$. Busza [2a] and others show that the total multiplicity, summed over all angles, varies approximately as

$$\langle n\rangle_{\text{h}A} \simeq \tfrac{1}{2}\,\langle n\rangle_{\text{hN}}(1+\bar{\nu})\,, \tag{1}$$

where $\bar{\nu}$ is the average nuclear thickness seen by the incident hadron measured in

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** This is an expanded version of an earlier paper describing the model (ref. [1]).

units of the mean free path for absorption * and $\langle n \rangle_{\mathrm{hN}}$ is the total multiplicity from hadron-nucleon interactions at the same energy.

(iii) Inclusive cross sections for rare processes such as ψ production and large mass di-muons [2b] vary more nearly as $A^{1.0}$. Similarly cross sections for producing hadrons at large angles and large p_{T} vary as A^1 or even faster [2c,d].

On the whole, inclusive production off nuclei looks much like that from hadron-nucleon collisions scaled by A^{α} where $0.5 < \alpha < 1.2$, depending on the process and the transverse and longitudinal momenta, p_{T} and p_{L}. A large nucleus such as lead is many interaction lengths thick for hadrons, and one might naively expect that a cascade eventually containing mostly low-energy hadrons would be set up within the nucleus. The data completely contradict this picture. This remarkable lack of cascading has been the subject of innumerable theoretical articles [3] which have explained qualitatively some aspects of the data.

2. Description of the model

I wish to show here that *all* aspects of the data can be understood at least qualitatively by a quark-scattering model in which the lack of cascading is a natural result of the fact that the force between quarks in a hadron is small for small separations. The incident hadron is pictured as a rather loosely bound composite of 2 or 3 valence quarks plus sea quarks and the nucleus as a sphere containing A nucleons ($3A$ valence quarks plus sea quarks). Particle production occurs mainly through the *elastic* scattering of a projectile quark on a target quark. This breaks up either or both hadrons, and the quarks involved eventually "dress" themselves into real hadrons which move generally in the direction of the parent quark. (A similar model has been used by Field and Feynman to describe large p_{T} production in hadron-hadron collisions [4].) The quarks in the beam particle may undergo any number of successive collisions in the nucleus; most of them involve small momentum transfers. Few of the incident quarks are absorbed in the nucleus and no new quarks appear until after the original ones are outside the nucleus, so that the quark flux can be considered constant through the nucleus.

As an example, let us consider a pion incident on a large nucleus. The model is crudely depicted in fig. 1. One of the quarks in the incident pion scatters twice in the nucleus. After the quarks leave the nucleus the forces responsible for the confinement of quarks within hadrons eventually cause new quark-antiquark pairs to form. These arrange themselves into real hadrons (just as they do in hadron-hadron collisions). I assume that the quarks "forget" how they were excited so that the hadron distributions are a function only of the incident momentum and the mo-

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* $\bar{\nu}$ can be thought of as the average number of collisions made by the incident hadrons. It can conveniently be parameterized as $\bar{\nu} = A\sigma_{\mathrm{in}}(\mathrm{hN})/\sigma_{\mathrm{in}}(\mathrm{h}A)$, the ratio of the effective cross-sectional area of A nucleons to that of the nucleus.

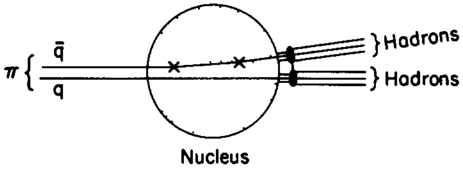

Fig. 1. An incident pion interacting with a nucleus *via* a double scattering of one of its valence quarks off quarks in the nucleus. The excited q$\bar{q}$ system dresses into real hadrons after the quarks leave the nucleus.

mentum transfer with no explicit A dependence. It is also assumed that the new hadrons formed generally follow the direction of the parent quark and that, at least at large p_T, successive scatters are for the most part incoherent so that their probabilities are uncorrelated.

It is specifically assumed that the quarks do not dress themselves into real hadrons (i.e., no new quarks materialize) until after the projectile leaves the nucleus. This assumption is forced by the data [2] which show that even at relatively large lab angles (14.6° in the experiment of Becker et al. [2d]), little or nor cascading occurs ★. A large nucleus has a diameter $\sim$12 fm, and we might question whether the quarks in the projectile could get so far apart without dressing. However this could come about because of the following reasons.

(i) Within the nucleus, effects analogous to polarization in a dielectric are likely to reduce the potential energy of the q$\bar{q}$ system significantly so that even at separations $\sim$10 fm it may be energetically unfavorable to produce a new q$\bar{q}$ pair.

(ii) In the rest system of the incident pion (presumably the one that matters) the incident nucleus is Lorentz contracted to a thickness $\sim R/\gamma_A$. If one of the quarks in the pion scatters it does not move very far along the beam direction from the unscattered quark before the nucleus has passed it by, unless a very large longitudinal momentum transfer occurs in the scattering. We assume this to be unlikely. In the direction transverse to the beam, a quark scattered at 14.6° in the lab (as in the experiment of Becker et al. [2d]) never gets more than $\sim$12 fm (tan 14.6°) $\simeq$ 3 fm away from the other while inside the nucleus.

3. Comparison with experimental data

Now that the model has been described, we can compare its predictions with the experimental data summarized in sect. 1. In this comparison I shall make no attempt

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★ Production cross sections were found to vary as A^1 or faster at large p_T. Appreciable cascading could lead to *less* production at large p_T from large nuclei, because the transverse momentum of the original particle (or quark) is shared by the secondaries. Thus the much rarer high p_T particles would cascade down to low p_T.

to explain the hadron-nucleon data Only the A dependence of the data shall be considered

(i) Production of fast forward particles occurs when one of the projectile quarks undergoes one or more small-angle scatterings off a target quark. The angular distribution of hadrons thus produced depends on the momentum transfer between the quark and the transverse momentum characteristic of the process of dressing the quarks into hadrons Except for the higher probability of multiple collisions of the projectile quarks in nuclei, we would expect angular distributions and multiplicities per interaction from nuclei in the projectile fragmentation region to be similar to those from nucleons. Since most of the quark-quark elastic scatterings are small-angle the effect of multiple collisions in large nuclei on the angular distributions should be rather small. We would expect the angular distribution of fast forward particles from large nuclei to be slightly broader because of multiple scattering of the projectile quarks. Thus the yield per interaction of fast forward particles should be *smaller* from a large nucleus than from hydrogen or a small nucleus Surprisingly there is little accurate data available to test this prediction. However, good data on production of Λ, $\overline{\Lambda}^0$, and K^0 from nuclei at small angles have recently become available [5]. Data for production off hydrogen are lacking so in fig 2 I show how the ratio of the Λ^0 yield per interaction from lead to that for ***beryllium*** varies with production angle and Λ^0 rapidity *. For small angles and high rapidities the Λ^0 yield per inelastic interaction from lead is ~0 5 that from beryllium while for larger angles and smaller momenta the ratio is close to unity This sort of behavior is expected in a multiple-collision model (if there is no cascading) and is difficult to explain without special assumptions in terms of most other models **. A detailed explanation would require a detailed knowledge of the q-q scattering probability as well as of the distributions of hadrons which result from the dressing of the quarks. A quantitative calculation of the small-angle behavior does not seem possible at present However, as shown below, it is possible to obtain reasonably quantitative agreement with the data at large p_T and production angles near 90° in the N-N c m s. where simplifying approximations are possible.

(ii) In this model the hadrons in the target fragmentation region are the products of the target quarks knocked out by the projectile quarks. These target quarks generally have momenta $\lesssim 1$ GeV/c and rarely will have sufficient energy to knock

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* Specifically the yield per interaction is defined as $\sigma_{\mathrm{in}}^{-1} E\, d^3\sigma/dp^3$ where σ_{in} is the total nucleon-nucleus inelastic cross section The latter were taken from 60 GeV data of Denisov et al. [9]

** There is of course the possibility that the reduced yield of Λ's at small angles is peculiar to Λ production and has nothing to do with multiple scattering However, in the author's opinion at least, the only reason this has not been seen in yields of other particles is that no one has looked in sufficient detail Most models would predict that forward Λ^0 production would have the same A dependence as that for producing other hadrons In any case the very detailed data of Eichten et al [2f] for $\pi^{\pm}$, $K^{\pm}$, and $p^{\pm}$ production by 24 GeV/c protons incident on nuclei show a behavior very similar to that for Λ's

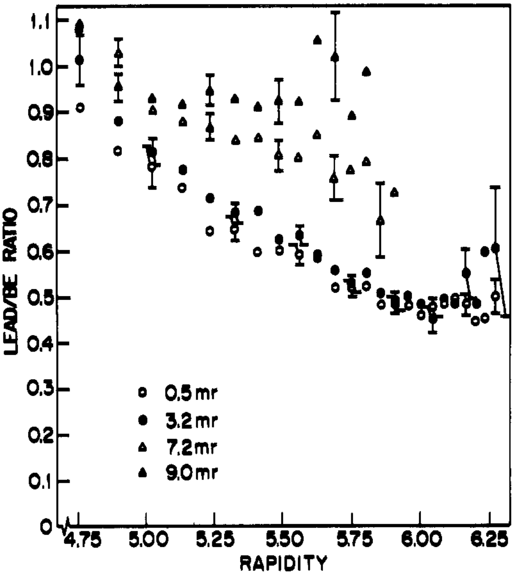

Fig. 2. Ratio of Λ^0 yields per interaction from lead to those from beryllium *versus* lab. rapidity for several laboratory angles. The data are for 300 GeV incident protons from the experiment of Skubic et al. [5]. Note the depletion of yields from lead at small angles and large rapidities. The "rapidity" is defined here as $\frac{1}{2}\ln((E+p)/(E-p))$ rather than in the conventional way.

out other target quarks on their way out of the nucleus. Comparing N-nucleus collisions with N-N collisions we have from the projectile quarks a multiplicity $\langle n_\mathrm{p}\rangle$:

$$\langle n_\mathrm{p}\rangle_{\mathrm{N}A} \simeq \langle n_\mathrm{p}\rangle_{\mathrm{NN}} ,$$

while from the target quarks:

$$\langle n_\mathrm{t}\rangle_{\mathrm{N}A} \simeq \bar{\nu}\langle n_\mathrm{t}\rangle_{\mathrm{NN}}$$

because there are $\bar{\nu}$ quark-quark collisions on the average. Thus, since $\langle n_\mathrm{p}\rangle_{\mathrm{NN}} = \langle n_\mathrm{T}\rangle_{\mathrm{NN}}$, in this model the total multiplicity from N-A (or high-energy $\bar{\mathrm{N}}$-A) scattering should be

$$\langle n\rangle_{\mathrm{N}A}/\langle n\rangle_{\mathrm{NN}} \simeq \tfrac{1}{2} + \tfrac{1}{2}\bar{\nu} . \qquad (2)$$

This prediction, while not unique to this model, is in excellent agreement with the experimental result, eq. 1 *. For π-N scattering the projectile only contains two valence quarks and the target nucleons three. If we weight the projectile and target

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* The good agreement must be considered somewhat fortuitous as there is some arbitrariness in identifying $\bar{\nu} \equiv A\sigma_{\mathrm{in}}(\mathrm{hN})/\sigma_{\mathrm{in}}(\mathrm{h}A)$ with the average number of q-q collisions and we are neglecting the competing effects of absorption of the target quarks and the secondaries they in turn produce.

hemispheres by the number of quarks involved, the prediction is

$$\langle n \rangle_{\pi A} / \langle n \rangle_{\pi \mathrm{N}} \simeq \tfrac{2}{5} + \tfrac{3}{5} \bar{\nu} \; . \tag{3}$$

Data presently available [2a] are not sufficiently accurate to distinguish the $\bar{\nu}$ dependences for different projectiles.

(iii) Since it is assumed that the projectile quarks for the most part only undergo small-angle scatterings, there is little attenuation of the incident quark flux in the nucleus. Thus rare processes (which are not easily undone by subsequent small-angle scatterings) should have *total* cross sections that vary approximately as A^1. Thus in this model we would expect an A^1 dependence for direct production of $\mu^{\pm}$ pairs (integrated over p_{T}). This is reasonably consistent with the data of Binkley et al. [2b] which show an $A^{0.85 \pm 0.05}$ dependence for muon pair production above the $(\rho + \omega)$ region for pairs with $p_{\mathrm{T}} \lesssim 1.5$ GeV/c. We would also expect production of ψ's and charmed particles to vary approximately as A^1, which is consistent with data [2b] on ψ production, which give $A^{0.93 \pm 0.04}$. This comes about because charmed quark pairs, once they are materialized from the sea of the projectile hadron, have a small probability for recombining.

In order to make a more quantitative test of the model I have calculated the A dependence of particle production at large lab angles and compared it with the data of Cronin et al. [2c] and Becker et al. [2d] for production at 90° in the N-N c.m.s. Their yields for π, K, p ... at fixed angle were fitted to an A^{α} dependence where α is a function of p_{T} (see fig. 4). In this model the A dependence is determined by multiple collisions of the projectile quarks, which I assume to be mostly incoherent. The probability of multiple collisions is determined by A and the q-q total cross section. With the assumption of additivity of quark cross sections I take the total q-q cross section to be one sixth of the π-N inelastic cross section or about 3.3 mb. This together with the nuclear radius determines the probability of single, double, triple, ... scattering. Sea quarks are not explicitly put into the calculation, but they are included implicitly through the use of a q-q total cross section equal to one sixth of the π-N inelastic cross section.

Given the above model, we could in principle calculate α as a function of p_{T}, p_{L} and particle type if we had a detailed knowledge of the p_{T} and p_{L} dependence of q-q elastic scattering and of how the dressing of quarks depends on these variables. Internal motion of the quarks in hadrons can be neglected provided it is done consistently (for example, by using the q-q scattering distributions of Field and Feynman [4] who also neglect it). Fermi motion of the nucleons in the nucleus is relatively unimportant since the momentum distributions within the various nuclei are not too different [3f]. Basically the calculation is a messy, but straightforward, Monte Carlo calculation.

Unfortunately this detailed knowledge of q-q scattering does not yet exist. Field and Feynman [4], in their analysis of large p_{T} phenomena, fit the data for $p_{\mathrm{T}} >$ 2 GeV/c with

$$\mathrm{d}\hat{\sigma}/\mathrm{d}\hat{t} = -2.3 \times 10^6 / (\hat{s}\, \hat{t}^3)\ \mu\mathrm{b} \cdot \mathrm{GeV}^6 , \tag{4}$$

where $\hat{s}$ and $\hat{t}$ refer to the two quarks and internal motion of the quarks is neglected. Fortunately, since α is determined from the *ratio* of yields for various nuclei, the calculated values are not too dependent on the details of the calculation. In the calculation it is assumed that the q-q elastic scattering depends only on p_T and not on θ_{cm} for large θ_{cm} *. Single, double, and triple scattering of the projectile quarks were considered Transverse momenta from successive scatters were combined in quadrature. Energy loss in successive scatters was neglected so that $\hat{s}$ was the same for each **.

The q-q single scattering distribution at large angles was assumed to depend only on $\hat{p}_T$ as follows

$$\mathrm{d}\hat{\sigma}/\mathrm{d}\hat{p}_T^2 \propto \mathrm{e}^{-b\hat{p}_T}\,, \qquad \hat{p}_T < 3\ \mathrm{GeV}/c\,, \tag{5a}$$

$$\propto \hat{p}_T^{-m}\,, \qquad \hat{p}_T > 3\ \mathrm{GeV}/c\,. \tag{5b}$$

The two distributions were normalized to the same value at 3 GeV/c. (see fig. 3.) Essentially nothing is known about q-q scattering at small p_T so the parameter b was adjusted to fit the data in fig 4. The constant m in eq. 5b was taken to be 6 to approximate the Field and Feynman dependence (eq. 4), which for constant $\hat{s}$ gives $\sigma \propto \hat{t}^{-3} \sim \hat{p}_T^{-6}$ ***. The overall normalization of eq (5) is determined by the condition that the integrated cross section = σ_{qq}.

With this input the calculation is a straightforward Monte Carlo calculation of incoherent multiple scattering of the incident quarks in a nucleus containing $3A$ quarks. Calculations were carried out for beryllium, titanium and tungsten targets as used in the experiments [2c,2d], and at each p_T the value of α was obtained from the ratio of the calculated quark scattering probabilities A good overall fit to the data was obtained with $b = 1.0\ (\mathrm{GeV}/c)^{-1}$ Fig 3 shows the resulting p_T distributions for single, double, and triple q-q scattering, each normalized so the integral over p_T is unity. In fig. 4 the calculated α's are compared to the data. The calculated values were found to be rather insensitive to all parameters except b, which determines the rate at which $\alpha(p_T)$ rises at small p_T The dashed curves in fig. 4 illustrate the effect of generous variations in the parameters The overall agreement with the data is very good, though the dependence on hadron type, which is not put into the model, cannot be reproduced.

In this model the p_T distribution of the hadrons is determined by that of the parent quarks. However, at present there is no simple way of relating p_T^{quark} with p_T^{hadron} At large p_T it is likely that one of the hadrons carries off most of the mo-

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* This assumption is supported by pion-inclusive production cross sections which are almost independent of θ_{cm} for $40° < \theta_{cm} < 140°$ (See fig 10 of ref 4)

** An incident quark elastically scattered through a c m angle of 90° as a result of two successive 45° scatters loses only ≈13% of its energy in the first collision if the incident and target quarks have equal mass.

*** Near 90° in the q-q c m s , $t \simeq 2p_T^2$ for scattering of quarks of equal mass

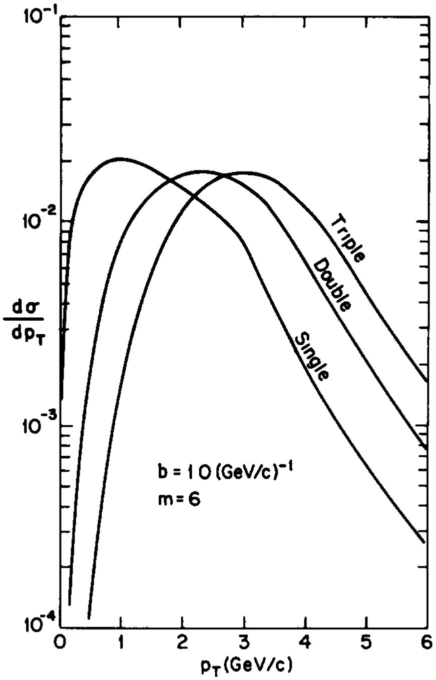

Fig 3 $d\sigma/dp_T = 2p_T\, d\sigma/dp_T^2$ for q-q single, double and triple scattering Each curve is normalized so that the integral over p_T is unity

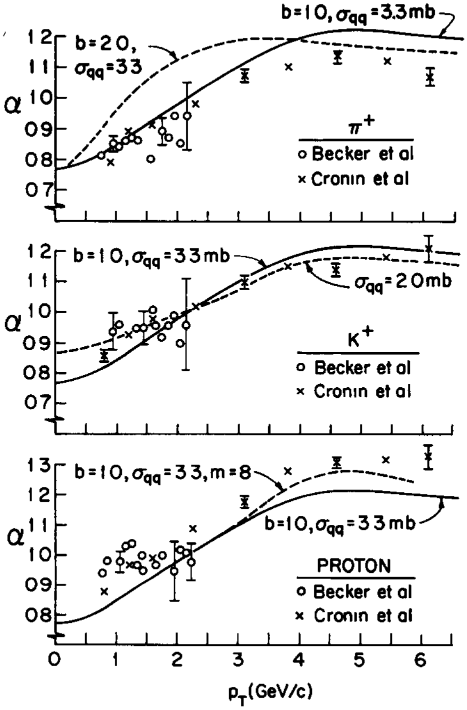

Fig. 4 Comparison of experimental data [2c,2d] for $\alpha(p_T)$ with the predicted dependence The dashed curves illustrate the sensitivity of the calculated curves to changes in the parameters, $m = 6$ for all the curves except where indicated.

mentum of the parent quark so $p_{\mathrm{T}}^{\mathrm{quark}} \simeq p_{\mathrm{T}}^{\mathrm{hadron}}$, but at small p_{T} we expect $p_{\mathrm{T}}^{\mathrm{hadron}} << p_{\mathrm{T}}^{\mathrm{quark}}$. For lack of a better alternative I have simply identified $p_{\mathrm{T}}^{\mathrm{hadron}}$ with $p_{\mathrm{T}}^{\mathrm{quark}}$. Because of this and other simplifying assumptions the value of $b = 1.0\ (\mathrm{GeV}/c)^{-1}$ can only be considered an effective value which makes the calculated $\alpha(p_{\mathrm{T}}^{\mathrm{quark}})$ mimic that observed for hadrons. At small p_{T} inclusive cross sections for production of hadrons in N-N collisions near 90° vary approximately as $e^{-bp_{\mathrm{T}}}$ with $b \simeq 5.8$ for π's and $b \simeq 2.7$ for K's and protons [6]. However each of the hadrons only carries off a fraction of the momentum of the parent quark. Thus an $e^{-1.0p_{\mathrm{T}}}$ distribution for the quarks might give a distribution more like $e^{-4p_{\mathrm{T}}}$ for the hadrons at a given lab angle.

4. Other predictions of the model

Other qualitative predictions of the model worth noting are the following.

(i) The dependence on incident particle, which comes about through the difference in quark content of the projectile, is expected to be generally small at high energies. At high energies ratios of yields for production off nuclei to those for production from nucleons are expected to be almost independent of energy. An example of this is the data shown in fig. 4. That of Becker et al. was taken at 28.5 GeV/c, that of Cronin et al. at 300 GeV/c.

(ii) Correlations between outgoing particles from nuclear targets should be similar to those from nucleon targets. However the correlations observed with large nuclei should be somewhat washed out by the effects of multiple scattering. If two large p_{T} hadrons are observed on opposite sides of the beam, the A dependence should be less rapid than for single hadron production. This is consistent with preliminary data from Fermilab [7] which show values of α smaller than those in fig. 4 for dihadron production when two large p_{T} hadrons on opposite sides of the beam are required.

(iii) In this model the production of a hadron with large p_{T} from a nucleon is likely to come from a single hard q-q scattering, while production off a large nucleus at the same p_{T} is likely to occur through several successive interactions, each at modest p_{T}. Thus, we would expect that production of a hadron with large p_{T} from a nucleus will be accompanied by a higher multiplicity (of softer particles) in the target region than production off a nucleon at the same p_{T}.

(iv) In this model, if it is assumed that the transverse momenta associated with dressing the quarks is small compared to the momentum transfer in the q-q collision, the hadrons produced tend to follow the direction of the parent quarks. Since scatterings involving large momentum transfer are rare, the angular region $\lesssim 90°$ in the hadron-nucleon c.m.s. is populated mostly by secondary hadrons produced from the projectile quarks and the region $\gtrsim 90°$ by hadrons produced from the target quarks. In this picture it is perhaps most convenient to think in terms of distribu-

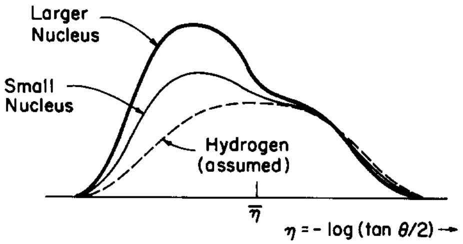

Fig 5 Schematic of the pseudorapidity distribution $dN/d\eta$ expected in the model for nuclei compared to that assumed for hydrogen The differential multiplicity at large η is reduced for nuclei because of multiple scattering of the projectile quarks For $\eta \lesssim \bar{\eta}$ the yields are proportional to $\bar{\nu}$

tions in angle or pseudorapidity [*], integrated over the momentum of the secondary hadrons Fig. 5 shows schematically the expected pseudorapidity distribution for a large nucleus if the distribution from hydrogen is assumed to be that shown by the dashed curve For large pseudorapidities (small lab angles) the yields from large nuclei are depleted by multiple scattering as discussed earlier. For $\eta \lesssim \bar{\eta}$, the mean value of η, yields from large nuclei increase approximately as $\bar{\nu}$ due to hadrons produced from the target quarks Busza et al [2a] find pseudorapidity distributions from nuclei very similar to that predicted in fig. 5. However they do not see the depletion in yield at large η. This is possibly due to low-momentum particles from the target quarks since this depletion is quite apparent in the data for Λ, $\bar{\Lambda}$, and K^0 yields of Skubic et al. [5] (some of which are shown in fig 2), especially for high-momentum particles, and in the data of Eichten et al [2f] for $\pi^{\pm}$, $K^{\pm}$ and $p^{\pm}$ yields [**]

5. Conclusions and comparison with other models

Predictions of the model described here seem to be in good agreement with all the data on the A dependence of production off nuclear targets, both at small and large angles. In the case of production near 90° in the N-N c.m.s. a semi-quantitative account of the data over a very large range in p_T is possible with only one parameter to set the scale in p_T. The large values observed for α at large p_T by Cronin et al. [2c] and Becker et al. [2d] are easily reproduced. The model gives quantitative agreement with the observed variation of multiplicity with A. In addition the A dependence of production at very small angles and its variation with pseudorapidity can be qualitatively understood.

Obviously far more work needs to be done, but it seems possible to understand

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[*] The pseudorapidity η is defined as $\eta = -\ln \tan \frac{1}{2}\theta_{\mathrm{lab}}$

[**] In the experiment of Busza et al. there was no particle identification so the data are dominated by pions.

particle production off nuclei in terms of a model similar in spirit to that used by Field and Feynman [4] to explain production from nucleons at large p_T. Once their model has been more completely developed and the parameters established for hadron-nucleon scattering, it should be straightforward to extend it to make quantitative predictions for hadron-nucleus scattering.It is important to note in this context that if the assumption that dressing takes place only after the scattered quarks leave the nucleus is correct, then the A dependence of inclusive production provides a way of learning about q-q scattering without having to understand how quarks dress into real hadrons.

In calculating the A dependence at large p_T I have assumed that successive q-q scatterings can be considered as incoherent. This assumption seems reasonable except at very small angles and small p_T where diffractive processes are important. It is interesting to note that the model described here has two time scales. The q-q scatterings are assumed to occur on a very short time scale, but the dressing of the quarks (and the appearance of new quarks) occurs on a long time scale $\tau > R/c$. The latter feature is, of course, what prevents the development of a cascade within the nucleus.

Other models have been able to account for some aspects of the data, but most are of extremely limited predictive power. The greatest effort has been devoted to the multiperipheral model [3b,c,d,h,i] and the closely related parton model [3g].

As generally formulated, the multiperipheral model (MPM) for nuclei is basically a one-dimensional model and makes predictions only for rapidity distributions. It is not at all clear how to connect these to the way the data varies with rapidity *and* angle. This is usually done by comparing the MPM predictions for rapidity with the experimental pseudorapidity distributions. If this is done, the predictions of the basic model do not agree with important features of the data. For example, the MPM without cuts predicts a plateau in rapidity which grows with energy, and $\sigma_{in}(\pi A)/\sigma_{in}(pA) = \sigma_{in}(\pi p)/\sigma_{in}(pp)$. Both these results disagree with the data, and the shape of the rapidity distributions are not as expected [2a]. In addition, Lehman and Winbow predict that in the MPM with cuts the spectrum of the leading particles will be the same as in hadron-nucleon collisions [3h], in disagreement with the data in fig. 2 and ref. [2f]. The most detailed treatment of a Regge model with poles and cuts is that of Koplik and Mueller [3i]. They predict that for large nuclei $(\sigma_{tot} - \sigma_{in}) << \sigma_{tot}$, in disagreement with the data which give $\sigma_{in}(n - Pb) \simeq 0.6\sigma_{tot}(n - Pb)$ [8]. This ratio of σ_{in} and σ_{tot} can come about in the theory [3i] if the differential multiplicity off large nuclei in the central region is much greater than that from nucleons. This however is not observed. Experimentally the ratio of multiplicities from heavy nuclei to that for hydrogen for pseudorapidities near the mean * is found to be <2 for tungsten [2e] with 300 GeV protons incident and for lead [2a] with 200 GeV π^+, while Koplik and Mueller require this ratio to be

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* I assume that the mean value of the pseudorapidity can be identified with the "central region" in the theory.

$\geqslant 3$ if $\sigma_{\mathrm{in}}/\sigma_{\mathrm{tot}} \simeq 0.6$ for large nuclei [3i]. In fact, the most natural prediction of the MPM is that the differential multiplicity [3c]

$$\sigma_{\mathrm{in}}^{-1}\, \mathrm{d}\sigma/\mathrm{d}y \propto A^{1/3},$$

which would give a lead/hydrogen ratio of 5.9 This value is only reached well into the target region in the 200 GeV data [2a].

Recently Capella and Krzywicki [3d] have described a multiple scattering model in which distinct constituents of the projectile undergo "parallel" interactions with different nucleons in the nucleus (an approach somewhat similar to that described here) With a particular prescription for adding rapidity densities and for the energy distribution of the constituents they are able to reproduce the pseudorapidity distributions of Busza et al [2a]. However their model is one-dimensional, and as in other such models it is necessary to make the peculiar correspondence between rapidity and lab angle (i.e., pseudorapidity). It is not at all clear that such a model can account even qualitatively for other important features of the data such as the close similarity in both momentum and angular distributions from nuclei and nucleons near the forward direction

The energy-flux model of Gottfried [3e] is also a one-dimensional model Like the MPM it has nothing to say about large p_{T} processes. It predicts rapidity distributions which vary with energy and A much like the experimental pseudorapidity distributions [2a] but does not predict the depletion at small angles from nuclei shown in fig 2 and ref [2f].

The coherent tube model [3a,j] and other models which try to explain the A dependence of the data at large p_{T} by means of collective effects involving many nucleons predict rapidity distributions from nuclei which extend to considerably lower values of y or η than those from nucleons [3b]. This is in disagreement with at least some of the data [2e,3a].

Kuhn [3f] has used a multiple scattering model to obtain a rough estimate of the variation of α with p_{T} which is similar to that given by the model I have discussed The literature is too extensive to allow an adequate summary of the many models here Andersson has recently given a very useful summary of many of the models and their strong and weak points [3a]

It is a pleasure to acknowledge helpful discussions with G. Kane, A. Mueller, W. Busza, K Heller and D. Burke.

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