Introduction

This talk covers new experimental results which have become available on the A-dependence of inclusive hadron scattering, with an emphasis on the projectile fragmentation region. This subject has received much attention in the past several years, in the hope that scattering from nuclear targets will provide a probe of the space-time structure of the interaction process.\[1\] The dependence of particle production on the incident particle type (or its constituents) and on the momentum of the newly formed hadrons is of fundamental interest in this regard.

Previous hadron-nucleus experiments have shown a weak, at most linear, increase of multiplicity of produced hadrons with increasing nuclear thickness.\[2\] In comparison with hadron-nucleon collisions, a slight but systematic depletion of the most energetic secondaries has been seen to grow with nuclear size. Many authors have pointed out that this behavior is characteristic of a long time scale for the formation or "hadronization" of the outgoing particles.\[3\]

Several previous measurements have been made of the A-dependence of inclusive processes in the beam fragmentation region. A study of proton interactions at 24 GeV by the Aachen, CERN, UCL, Orsay, Torino collaboration\[4\] found less attenuation and less dependence on Feynman x for outgoing pions than for protons. The Fermilab, Northwestern, Rochester collaboration measured the production of charged particles in neutron-nucleus interactions around 300 GeV.\[5\] They fitted their data to a power law, A^α, and found a weak monotonic decrease in multiplicity with increasing rapidity. The inclusive production of Λ^0 and K^0 in proton-nucleus collisions at 300 GeV has been measured by a Michigan, Rutgers, Wisconsin collaboration,\[6\] who have observed a gently increasing attenuation with increasing Feynman x. A
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similar behavior was found for neutron production by 400 GeV protons on nuclei in an experiment at Fermilab by another Michigan group.[7]

Most recently, two particular classes of models have appeared in the literature dealing with particle production in hadron-nucleus collisions. First a variety of additive quark models have been described in which independent constituent quarks interact or are "wounded" in a collision with a nucleon in the nucleus.[8,9,10,11] The process proceeds as indicated for an incident pion in Figure 1 where the development of secondary particles from the wounded quark is assumed to be independent of the hadronization of the spectator quark(s). The projectile fragmentation region is expected to be dominated by the products of the spectator system which should be characterized by a long formation time.

![Figure 1](image)

The second class of models treat the constituents collectively and describe the interaction in terms of multiple collisions by the incident hadron with nucleons in the nucleus.[12,13,14] According to these models, the attenuation observed in the projectile fragmentation region reflects energy-momentum constraints in the partition of energy in the subcollisions. The usual description of these models involves $\nu$, the number of collisions, either through the probability of $\nu$ collisions $P_N(\nu)$, or by the average number of collisions defined for incident hadron $h$ by:

$$\bar{\nu}_h = \frac{A \sigma_{hp}}{\sigma_{hA}} .$$

New Results

I would like to call to your attention some new data on hadron-nucleus interactions from the NA5 collaboration at the
CERN SPS.[15] This group has measured the differential multiplicity as a function of rapidity for 4000 events from runs taken with 200 GeV protons and antiprotons incident on hydrogen and xenon. The data are shown in Figure 2 along with the prediction of a collective multiple collision model. The results show a clear attenuation in the highest two units of rapidity which correspond to the projectile fragmentation region. They also indicate a remarkably high multiplicity in the target fragmentation region, especially so in view of the fact that the authors have excluded protons with momenta less than 1 GeV/c and nuclear fragments from the sample.

![Figure 2. Ratio of xenon and hydrogen differential cross sections for protons and anti-protons.](Ref. 15)]

I would like to turn now to the main topic of my talk, a report on results of a Fermilab experiment in which I have participated.[16] We have performed an experiment to measure the inclusive process \( h + A \rightarrow h' + x \) where \( h \) was either \( \pi^+ \), \( K^+ \), or \( p \); \( h' \) was \( \pi^\pm \), \( K^\pm \), or \( p \); and \( A \), the nuclear target, was either C,
Al, Cu, Ag, or Pb. This experiment was a continuation of an extensive study of particle production in hN interactions.[17,18] Since the apparatus was essentially identical in the two experiments, an accurate comparison between hN and hA interactions, free of many systematic errors, is possible.

![Diagram](image)

Figure 3. Layout of equipment in Fermilab Single Arm Spectrometer.

The experimental apparatus consisted of the Fermilab M6E beam line and the Single Arm Spectrometer Facility as indicated in Figure 3. An incident beam of 100 GeV/c was used. The production of the fast secondary, h', was measured over the Feynmann x range $0.3 \leq x \leq 0.88$ and the transverse momentum range $0.18 \leq p_T \leq 0.5$. Data were taken simultaneously for the nine reaction types ($\pi\pi$, $\pi K$, $\pi p$, etc). The details of the instrumentation of the beam line and spectrometer have been summarized in Ref. 17. Good $\pi$-K-p separation was achieved over the entire kinematic range using the eight Cerenkov counters of the facility. The targets used in the experiment were as follows:

<table>
<thead>
<tr>
<th>Target</th>
<th>Thickness (g/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>1.37, 3.93, 5.79</td>
</tr>
<tr>
<td>Al</td>
<td>5.99</td>
</tr>
<tr>
<td>Cu</td>
<td>2.89, 5.94, 9.94</td>
</tr>
<tr>
<td>Ag</td>
<td>6.71</td>
</tr>
<tr>
<td>Pb</td>
<td>2.06, 4.00, 7.38</td>
</tr>
</tbody>
</table>

Data was taken principally with thick targets, with thinner ones used for finite thickness corrections.
In a manner similar to that described in Ref. 17, the interaction rates were corrected for particle absorption and decay in the spectrometer, finite target thickness, multiple scattering losses in the spectrometer, particle misidentification and track reconstruction inefficiencies. The corrected rates were then used to obtain, for every channel, the invariant differential cross section $E \frac{d^{3}\sigma}{dp^{3}}$ (mb/GeV$^2$ per nucleus).

I will discuss the most significant features of the invariant cross sections. Complete numerical results will be published elsewhere, including some information on multiplicities and angular distributions of associated particles.

Figure 4 illustrates the dependence of $E/A \frac{d^{3}\sigma}{dp^{3}}$, the differential cross section per nucleon measured at $p_T = .30$, on $A$ and Feynman $x$. The errors indicated are statistical. Other channels exhibit similar trends but with lower statistical precision. The overall normalization uncertainty is estimated to be 10%. The systematic uncertainty due to particle misidentification in the reactions with an outgoing kaon is less than 5%. The figures include the previously measured data for hydrogen at the same kinematic points. For all channels we note increasing
Figure 4. Invariant differential cross section per nucleon vs Feynman x at fixed $p_T = 0.3$. Hydrogen data from Ref. 17; nuclear target data from Ref. 16. Dashed curves estimate of resonance contribution to double charge-exchange reaction on hydrogen (Ref. 18).
attenuation as a function of A. In Figures 4a and 4b a shoulder is apparent in the invariant cross section centered around \( x \approx .7 \), which is clearly visible for all A in the reaction \( \pi^+ \rightarrow \pi^- \). A similar effect seems to show up for the \( \pi^+ \rightarrow \pi^+ \) reaction on the heavier nuclei. The dashed curve shown in Figure 4b is an estimate of the possible contribution from diffractive \( p^0 \) and \( f^0 \) production to the hydrogen cross section from Ref. 18.

We have fitted the A-dependence of the cross sections to the empirical form

\[
E \frac{d^3\sigma}{dp^3}(x, p_T, A) = \sigma_0(x, p_T)A^{\alpha(x, p_T)}. \tag{2}
\]

Hydrogen data were not included in the fits. This functional form is not chosen on any particular theoretical basis. We have found that for some data, in particular the high statistics \( \pi^+ \rightarrow \pi^+ \) data at \( x = .88 \), the fit is particularly poor, as indicated in Figure 5.
The fitted values of the power $\alpha$ are displayed in Figure 6 as a function of $x$ and $p_T$ for the channels with reasonable statistics. The results from interpolation of the 24 GeV data of Ref. 4 are shown for comparison for the reactions with an incident proton. Our data seems to show a slightly milder $x$ dependence than the 24 GeV data. In general, a comparison of the $p$ and $\pi^-$-induced reactions shows that for any produced particle the attenuation in nuclear matter is greater for incident protons. In the $\pi^+\pi^-$ channel, in particular $\pi^+\pi^-$ at $p_T = .3$, the same region near $x = .7$ which exhibited a change in shape of the momentum spectrum seems to show a slight decrease in the attenuation. This characteristic might arise from a diffractive production mechanism as mentioned above.

**Additive Quark Fragmentation**

The application to projectile fragmentation data of a model of hadron-nucleus interactions involving constituent quarks has been discussed by Bialas et al. [9,19] They have argued that this data should be dominated by the fragmentation of spectator quarks. Their application of this model to the 300 GeV strange particle production data of Ref. 6 yields an estimate of the fragmentation functions of the constituent quarks in the proton. The authors conclude that for values of Feynman $x$ greater than 0.2 the process is entirely dominated by spectator quark and di-quark fragmentation.

For the case of an incident pion they give the following expression for the differential multiplicity:

$$n_A(p) \equiv \frac{1}{\sigma_{inel}} \int dp_T^2 \ E \frac{d^3\sigma}{dp^3} = w_A n_w(p) + (2-w_A)n_s(p) ,$$

(3)

where $n_w(p)$ and $n_s(p)$ are the fragmentation functions of a wounded and spectator quark respectively. The quantity $w_A$ is the average number of quarks wounded in interactions with nucleus A, given by

$$w_A = \frac{N_h \bar{\sigma} qA}{\bar{\sigma}_{nA}} .$$

(4)

$N_h$ is the number of constituents in the projectile; consistent with $N_h = 2$ for pions and $N_h = 3$ for protons. [9] The inelastic, nondiffractive quark and hadron cross sections on
Figure 5. Fitted values of $\alpha$ from power law fits to invariant differential cross section. Dashed lines are interpolation of results from Ref. 4.
nucleus $A$, $\bar{\sigma}_{qA}$ and $\bar{\sigma}_{nA}$, have been obtained from the optical formula

$$\bar{\sigma}_{iA} = \int d^2b \left| 1 - \left[ 1 - \bar{\sigma}_{iH} D_A(b) \right]^A \right|,$$

where

$$D_A(b) = \int dz \rho_A(b, z)$$

for the nucleus density $\rho_A(b, z)$. The quantity $w_A$ can be related to the probability $P_A^{(i)}$ of $i$ quarks wounded in the interaction. For pions these relationships are

$$P_A^{(1)} = 2 - w_A$$

$$P_A^{(2)} = w_A - 1.$$

The result of a calculation by Anisovich et al. [8] of these probabilities for pions as a function of $A$ is shown in Figure 7.

The data we have obtained for pion induced reactions have been fitted to this parameterization. In so doing, we have been unable to integrate over $p_T$, but we expect this to be unimportant since we have already seen that the power law parameterization was similar from $p_T = .18$ to $p_T = .50$. Figure 8 shows the results of fits of the quantity.
Figure 8. Fitted values of fragmentation functions of spectator and wounded quarks (after Ref. 19).
\[ F_A(x) = \frac{E}{\sigma_{inel}^{(A)}} \frac{d^3\sigma}{dp^3}(x) \quad \text{(at fixed } p_T) \]

to the form

\[ F_A(x) = w_A F_w(x) + (2-w_A) F_s(x) \quad \text{(7)} \]

The values of \( \sigma_{inel}^{(A)} \) have been interpolated from Fermilab data at 60 and 200 GeV.[20] The quality of the fits were generally as good as the power law fits given above. The \( \pi^+ + \pi^+ \) data at \( x = 0.88 \) was fit with a satisfactory \( \chi^2 \), but the value of \( F_w(x) \) is negative by approximately 7 standard deviations. With this exception, the data exhibit characteristics expected for fragmentation dominated by spectator quarks. The contribution from wounded quarks is significant only below \( x \approx 0.4 \), and the channels with a "favored" quark spectator show enhanced values of \( F_s \) at large \( x \). A noteworthy exception again occurs for \( \pi^+ + \pi^- \) at low \( p_T \), where emergence of an "unfavored" quark from a resonance decay might be responsible for the observed effect.

In a recent preprint[21] and in the next paper to be presented Bia\'zas compares the predictions of his additive quark model and that of collective multiple collision models for the behavior near \( x = 1 \) of \( R_A = n_A(p)/n_H(p) \), where the \( n \)'s are defined in Equation (3). We have calculated the analogous quantity without integration over \( p_T \): "\( R_A'(x) = F_A(x)/F_H(x) \). This comparison, which is shown in Figure 9 and will be discussed by Dr. Bia\'zas, raises a question about the validity of the very high \( x \) data for such comparisons. The same data at \( x = 0.88 \) for \( \pi^+ + \pi^+ \) which yielded poor fits above is involved here also.

Conclusions

In summary, I would make the following observations about these results:

1. For all reactions measured in the beam fragmentation region \( (x > 0.3) \), the effectiveness of nucleons for particle production decreases with \( A \).

2. This attenuation is less for incident pions than for
protons. There seems to be little difference between incident antiprotons and protons in the CERN result.

3. Very little variation with $p_T$ of the $A$-dependence over the range covered (180-500 MeV/c).

4. At the highest $x$ value measured (0.88), results tend toward the limit of one collision (peripheral). Neither the fit to a power of $A$ nor the fit to constituent quark fragmentation functions were satisfactory for the high precision $\pi^+ \rightarrow \pi^+$ data at this kinematic point.

5. Both $\pi \rightarrow \pi$ reactions show a shoulder in the Feynman $x$ distribution which may exhibit slightly less attenuation in the nucleus. This region may be populated by diffractive resonance production at high $x$.

Finally clarification of the validity of models as $x$ closely approaches $x = 1$ might help discriminate between various mechanisms of projectile fragmentation on nuclei.
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