Nuclear Effects in Semi-inclusive Hadron Production

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Semi–inclusive production of charged hadrons ($\pi^+$, $\pi^-$, $K^+$, $K^-$, $p$, and $\bar{p}$) in deep inelastic scattering has been studied by the HERMES experiment. Using the 27.5 GeV positron beam at DESY, the hadron multiplicity from \textsuperscript{12}N and \textsuperscript{34}Kr has been measured and compared to that from deuterium. Significant nuclear effects have been observed suggesting a modification of the quark fragmentation process in nuclei.

1. Introduction

In the deep inelastic scattering (DIS) process, the production of hadrons can be viewed as the interaction of a virtual photon with a quark in the target nucleon (or nucleus) and the subsequent hadronization of that quark.Assuming these two processes are independent, the cross section can be written as a product of the quark distribution function, $q_f(x)$, and the fragmentation function, $D(z)$, weighted by the quark charge squared ($e_f^2$),

$$\sigma \sim \sum_f e_f^2 q_f(x) D_f^h(z).$$  \hspace{1cm} (1)

The quark distribution function in the above equation describes the probability to find a quark with flavor $f$ and a fraction $x$ ($x = Q^2/2m\nu$) of the nucleon momentum, while the fragmentation function describes the probability of that quark to form a hadron of type $h$ with a fraction $z$ ($z = E_h/\nu$) of the energy of the virtual photon.

The formation of hadrons in deep inelastic scattering can be modified in the nuclear environment. In the simplest picture, the struck quark propagates a certain distance before forming a hadron. Either the quark or hadron may interact with the additional hadrons in the nucleus. Whether the quark–hadron or hadron–hadron interactions dominate will depend on the hadron formation time $\tau_f$.

Nuclear effects in deep inelastic hadron production can be studied via the multiplicity ratio, $R_M^h$.

This ratio measures the number of hadrons (of type $h$) per inclusive DIS event produced from a target with mass $A$ compared to the hadron production rate from deuterium,

$$R_M^h(z, \nu) = \left( \frac{\frac{1}{A} \frac{d\sigma}{d^4q}}{\frac{1}{D} \frac{d\sigma}{d^4q}} \right)_D = \left( \frac{\frac{1}{A} \frac{dN_h}{d^4q}}{\frac{1}{D} \frac{dN_h}{d^4q}} \right)_D,$$ \hspace{1cm} (2)

where $N_c$ is the number of inclusive electrons and $dN_h/d^4q$ is the number of hadrons of type $h$ in a given $\nu$ and $z$ bin. The DIS normalized semi–inclusive yield for a particular target can be written in terms of fragmentation functions and quark distribution functions,

$$\frac{1}{N_c} \frac{dN_h}{d^4q} = \frac{\sum_f e_f^2 q_f(x) D_f^h(z)}{\sum_f e_f^2 q_f(x)}.$$ \hspace{1cm} (3)

Hence, the multiplicity ratio defined in Eq. 2 is sensitive to potential modifications to the fragmentation process in nuclei.

2. Models of Hadron Attenuation in Nuclei

Below we will discuss a few of the models that have been used to describe attenuation in the deep inelastic production of hadrons.
2.1. One Time–Scale Model

Perhaps the most intuitive description of hadron attenuation in nuclei, the one time–scale model assumes that the struck quark propagates for a mean time $\tau_f$ before the formation of the hadron [1]. In this model, the formation time is proportional to the energy of the created hadron and the multiplicity ratio is given by,

$$R_M^b = 2\pi \int_0^\infty \int_{-\infty}^{\infty} dl \; \rho_A(b, l) \left[ P_A(b, l) \right]^{A-1} (4)$$

where $\rho_A$ is the nuclear density and $P_A$ is the probability to have no interaction as the quark and/or hadron propagates in the nucleus. This probability involves the quark–hadron cross section, $\sigma_q$, and the hadron–hadron cross section, $\sigma_h$. It is assumed that $\sigma_q << \sigma_h$ while $\sigma_h \approx 20 \text{ mb}$. Hence, this model really only involves one degree of freedom, the hadron formation time, $\tau_f$.

2.2. Two Time–Scale Model

The two time–scale model extends the one time–scale model by assuming that the struck quark does not necessarily form the final hadron directly, but may instead form some quasi-hadron in an intermediate state [2]. In this model $\tau_f$ still describes the total formation time, i.e., the time between the hard interaction with the struck quark and formation of the final hadron, however an additional time, $\tau_i$ describes the time between the hard interaction and the formation of the intermediate hadronic state.

The multiplicity ratio is calculated similarly to Eq. 4, however the no–interaction probability, $P_A$, now includes the contribution from the pre–hadron cross section, $\sigma^*$.

It should be pointed out that both the one and two time–scale models are likely over–simplified pictures in that the hadronic interactions are treated as purely absorptive. An improved version of the two time–scale approach that treats the hadronic interactions in a more complete fashion can be found in Ref. [3]. However, the simple one and two time–scale (purely absorptive) models are useful in that, with the appropriate assumptions, they can provide a reasonable description of the experimental data (as will be seen later) while being relatively easy to calculate.

2.3. Gluon Bremsstrahlung

The gluon bremsstrahlung description of hadron attenuation in nuclei assumes that the final hadron is formed when the struck quark combines with a $q$ or $\bar{q}$ formed from a radiated gluon [4]. Large $z$ hadrons retain much of the energy of the struck quark – hence, in the case where gluon bremsstrahlung is significant, the number of high $z$ hadrons will be reduced. In this model the emission of gluons is enhanced in the nuclear environment, leading to a suppression at high $z$ of the multiplicity ratio. In contrast to the one and two time–scale models, hadron scattering in the final state is not significant in the gluon bremsstrahlung model due to color transparency effects.

2.4. Parton Multiple Scattering

The hadron multiplicity in nuclei may also be affected by parton multiple scattering. In this case, the fragmentation function is modified via quark rescattering with partons in other nucleons [5]. The dominant contribution in this case comes from terms involving gluon radiation from the struck quark combined with rescattering from gluons from another parton.

3. Hadron Multiplicity Measurements at HERMES

The HERMES experiment has measured the hadron multiplicity ratio, $R_M^b$, from $^{14}\text{N}$ and $^{84}\text{Kr}$. Positrons of 27.5 GeV in the HERA storage ring at DESY were incident on gas targets (nuclear and deuterium) while the scattered positrons and produced hadrons were detected in the HERMES spectrometer. The HERMES spectrometer consists of several sets of wire chambers for tracking, with a TRD, calorimeter, and Čerenkov detector for particle identification [6]. Prior to 1998, a threshold gas Čerenkov was used, allowing the separation of pions from other hadrons for 4 GeV $< p_\pi < 13.5$ GeV. In 1998, a dual radiator ring imaging Čerenkov detector (RICH) was installed, allowing clean identification of pions, kaons, and protons separately over a momentum range of 2.5 GeV $< p < 15$ GeV (for pions and kaons) or 4 GeV $< p < 15$ GeV (for pro-
Figure 1. Charged hadron multiplicity ratio vs. \( \nu (z > 0.2) \) for HERMES \(^{14}\text{N} \) data and data from other experiments. The long-dashed curve is a one time-scale calculation with \( \sigma_q = 0.75 \) mb and \( \sigma_h = 20 \) mb and \( \tau_h \propto E_h \).

The data were analyzed as follows. Scattered positrons with \( Q^2 > 1 \) GeV\(^2\) and \( W > 2 \) GeV were selected to ensure that the kinematics of the process were in the deep inelastic regime and to avoid the nucleon resonance region. A further constraint of \( y = \nu/E < 0.85 \) was used to avoid having to apply large radiative corrections. The produced (charged) hadrons were identified either as a whole or separated by species as noted above. Hadrons from target fragmentation were suppressed by requiring \( z > 0.2 \). Since \( \nu \) and \( z \) are partially correlated in the HERMES acceptance, this \( z \) constraint, combined with the minimum hadron momentum constraints noted above implies \( \nu > 7 \) GeV.

Figure 1 shows the multiplicity ratio for \(^{14}\text{N} \) as a function of \( \nu \) for all charged hadrons with \( z > 0.2 \) \cite{7}. Also shown are data from SLAC \cite{8} and CERN \cite{9} for Cu (top panel) and \(^{12}\text{C} \) (bottom panel). The dashed-dot curve is one time-scale calculation while the other curves are two time-scale calculations for various values of \( \sigma^* \) (note that \( \sigma^* = \sigma_h \) is equivalent to a one time-scale calculation, with a different definition of \( \tau_f \)). The details of each calculation are listed in Table 1. Clearly, when examining the \( \nu \) dependence and without differentiating between hadron types, these simple models can fit the data well.

The \( z \) dependence of the multiplicity ratio, Figure 2. Multiplicity ratios for all charge hadrons (closed squares) and charged pions (open circles) as a function of \( z \). The solid line is a gluon bremsstrahlung calculation while the other curves are one (dashed–dotted and dotted lines) and two (long–dashed line) time-scale calculations.

Table 1

<table>
<thead>
<tr>
<th>curve</th>
<th>( \tau_f ) (fm/c)</th>
<th>( \sigma_q )</th>
<th>( \sigma^* )</th>
<th>( \sigma_h )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( c_h z \nu )</td>
<td>0</td>
<td>N/A</td>
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<td></td>
</tr>
<tr>
<td>( (1 - \ln(z)) z \nu / (\text{ke}) )</td>
<td>0.75</td>
<td>20</td>
<td>20</td>
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</tr>
<tr>
<td>( (1 - \ln(z)) z \nu / (\text{ke}) )</td>
<td>0</td>
<td>20</td>
<td>20</td>
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</tr>
<tr>
<td>( (1 - \ln(z)) z \nu / (\text{ke}) )</td>
<td>0</td>
<td>0</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>( c_h (1 - z) \nu )</td>
<td>0</td>
<td>N/A</td>
<td>20</td>
<td></td>
</tr>
</tbody>
</table>
however, reveals the weaknesses in the one and two time-scale models. Fig. 2 shows the $z$ dependence of the HERMES $^{14}$N multiplicity ratio for all hadrons and pions [7]. The solid curve is a gluon bremsstrahlung calculation for pions and agrees with the trend of the data rather well. It is interesting to note that the two time-scale model calculation with $\sigma^* = \sigma_b$ (long-dashed curve) which agreed well with the $\nu$ dependence seen in Fig. 1 does not give the correct $z$ dependence. However, by using an ad-hoc expression for the formation time, $\tau_f \propto (1 - z)\nu$, the correct $z$ dependence can be recovered.

Newer HERMES data on $^{84}$Kr allows one to examine the mass dependence of these effects. Fig. 3 show the multiplicity ratios for $^{84}$Kr and $^{14}$N as a function of $z$. Clearly, the reduction in hadron multiplicity seen in the $^{14}$N data is even larger in the $^{84}$Kr. This increase in the attenuation $(1 - R_A)$ at large $z$ is consistent with modified fragmentation function predictions of Guo and Wang [5]. Furthermore, they predict the attenuation should increase quadratically with the nuclear size (i.e. $\propto A^{2/3}$) which is consistent with

The transverse momentum ($p_t$) dependence of the HERMES multiplicity ratios is also consistent with the idea of parton multiple scattering leading to modification of the fragmentation functions. An enhancement of hadron multiplicities in proton-nucleus and nucleus-nucleus collisions (the so-called Cronin effect) has been explained in terms of parton multiple scattering [10] and a similar effect should apply in semi-inclusive lepton nucleus scattering [11]. The $p_t^2$ dependence of the multiplicity ratios is shown in Fig. 4 where an enhancement of the ratio at $\approx 1$ GeV$^2$ is clearly evident for both the $^{14}$N and $^{84}$Kr data.

Finally, it should be noted that with the excellent hadron identification capabilities of the RICH, the HERMES experiment has also been able to measure the multiplicity ratios for several types of particles separately. These results (available only for the $^{84}$Kr data as the RICH was not yet installed during the $^{14}$N data taking) are shown in Fig. 5. This data set will serve to further constrain models of semi-inclusive hadron
production in nuclei. In particular, the different hadron-hadron cross sections ($\sigma_{\pi/K} \approx 20$ mb while $\sigma_{p/\gamma} \approx 40 - 60$ mb) will help disentangle fragmentation function modification effects from hadron rescattering effects. In fact, recent calculations [12] for $\pi^\pm$ and $K^\pm$ that incorporate both fragmentation function modifications and nuclear absorption show very good agreement with the HERMES $^8$Kr data.

4. Considerations for Neutrino Scattering Experiments

In the context of low energy (few GeV) neutrino experiments, one is not so much concerned with the physics of hadron attenuation in semi-inclusive DIS as the effects on particle rates. Furthermore, it is likely that one need not model these effects with a great deal of precision. While the large energy spread of neutrino beams will ensure that deep inelastic scattering ($Q^2 > 1$ GeV$^2$, $W > 2$ GeV) will play some role, it will certainly not be the dominant process.

Furthermore, the majority of semi-inclusive hadrons produced in DIS are pions, so one need not worry about the different attenuation ratios for the different species of hadrons. That said, a good first step in taking these processes into account is likely the one-time-scale parameterization ($\tau_f \propto (1 - z)\nu$) shown in Fig. 2 (dotted line). The $A$ dependence could then be taken into account via a simple $A^{2/3}$ scaling in $1 - R_A$.

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