$K_s^0$ Hadronization Following DIS at CLAS

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The hadronization of $K^0$ particles was measured in semi-inclusive deep inelastic scattering (SIDIS) kinematics for several nuclear targets using the CLAS detector. Multiplicity ratios and $\Delta p_T^2$ values were extracted from the data. These results may be compared with similar values for $\pi^+$ hadronization from CLAS (at the same kinematics) and $K^+$ hadronization from HERMES (at higher energy transfer). The physics goal of these measurements is to understand the space-time evolution as the struck quark becomes a full-blown hadron as it propagates through nuclear matter.

1 Introduction

The CLAS experiment called eg2 was run with a variety of nuclear targets using a 5.5 GeV electron beam from the continuous electron beam accelerator facility (CEBAF) at Jefferson Lab [2]. The goal of this experiment is to measure observables related to the propagation of a quark struck by the virtual photon from deep inelastic scattering (DIS) through cold nuclear matter. These results will be contrasted with quark propagation through hot QCD matter, sometimes called the quark-gluon plasma (QGP), formed in relativistic heavy ion collisions (RHIC). Quarks from RHIC are tagged by back-to-back “jets” of high energy hadrons formed by hard quark-quark collisions. In contrast with RHIC results, where the quark propagation is severely damped by passage through the QGP, the DIS data from HERMES [3] suggest that the struck quark propagates more easily (compared with fully formed mesons) through cold nuclear matter.

The measured quantities of the SIDIS measurements are the squared four-momentum transfer ($Q^2$) and energy transfer ($\nu$) from the scattered electron and the energy fraction ($z = E_h/\nu$) and transverse momentum ($p_T$) of the leading hadron. By comparing the $z$ and $p_T$ distributions of pions and kaons from a deuterium target with that from various nuclear targets, the quark propagation and formation into a hadron can be inferred. Theoretical predictions in a given model provide guidance to interpret the experimental results. In this way, the space-time characteristics of QCD (in the process of forming a hadron from the struck quark) becomes accessible [4].

Ratios of the number of hadrons detected, normalized to the number of DIS events in a given kinematic bin of $Q^2$ and $\nu$, for a nuclear target divided by the same quantities for a deuterium target are one quantitative measure of the effects of propagation through cold nuclear matter. The measured multiplicity ratio is given by:

$$ R = \frac{(N_h(\nu, Q^2, z)/N_e(\nu, Q^2))_A}{(N_h(\nu, Q^2, z)/N_e(\nu, Q^2))_D} $$

where $N_h$ is the number of hadrons of type $h$ (here, $h$ is a pion or a kaon) with energy fraction $z = E_h/\nu$ measured for semi-inclusive final states (SIDIS), $N_e$ is the number of

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electrons in DIS, and the numerator is for a given nuclear target $A$ while the denominator is for deuterium $D$. Because $R$ is a super-ratio (a ratio of ratios), many systematic effects cancel. For example, the detector efficiency to measure an electron at a given kinematics ($\nu$ and $Q^2$) will be the same (to first order) for targets $A$ and $D$. Similarly, the detection efficiency of a pion with energy fraction $z$ in a given kinematic bin will be the nearly same for targets $A$ and $D$. Small effects due to differences in the geometry of the two targets can be corrected using Monte Carlo simulations. The interpretation of the multiplicity ratio in terms of the physics of the formation time of a given hadron $h$ can be obtained using theoretical models such as the BUU model [5].

Another observable, the difference of the mean-square of the transverse momentum of a hadron, $\langle p_T^2 \rangle$, measured from the axis of the virtual photon momentum $\vec{q}$, for a nuclear target minus that for a deuterium target is given by

$$\Delta p_T^2 = \langle p_T^2 \rangle_A - \langle p_T^2 \rangle_D .$$

This quantity, according to theoretical models, is sensitive to gluonic radiation by the quark before it forms into a hadron [6]. This can be plotted as a function of $\nu$ for various nuclei, $A$, and can be compared with theoretical predictions [6] of the quark gluonic energy loss,

$$\left( \frac{dE}{dx} \right)_{\text{medium}} = \frac{3}{4} \alpha_s \Delta p_T^2 . \quad (1)$$

where $\alpha_s$ is the strong coupling constant. The mechanism of energy loss is primarily medium-stimulated gluon radiation, although collisional losses are also treated. Although Ref. [6] considers ‘cold’ nuclear matter they do not specifically address data from nuclei, as was done by Ref. [7].

2 Preliminary Results

By comparing these two quantitative measures with theoretical calculations over a variety of kinematics, models of hadronization can be tested. The HERMES experiment has already published the nuclear attenuation ratios for several types of hadrons at DIS kinematics in the range $8 < \nu < 23$ GeV [3]. The CLAS data are for a lower energy range, with $2 < \nu < 5$ GeV, corresponding to shorter hadron formation times. At HERMES kinematics, calculations suggest [3] that the quark propagates through the full nucleus, followed by hadron formation outside of the nuclear radius. At CLAS, we expect to see hadron formation inside the nuclear radius, at least for heavier nuclear targets (larger $A$).

Figure 1: Preliminary results for kinematic dependence of the super-ratio $R$ for $\pi^+$ hadronization detected in CLAS (updated analysis from Ref. [4]).
Preliminary results for $\pi^+$ produced at CLAS [4], shown in Fig. 1, indicate little dependence of the multiplicity ratio $R$ on the DIS variables $\nu$ and $Q^2$ for a given nuclear target, whereas $R$ does depend on $z$ and $p_T^2$. Since the attenuation of $R$ does depend on the nucleus at these kinematics, the results of Fig. 1 suggests that the average hadron formation length is shorter than the radius of Pb. Nuclear multiplicity ratios cannot be explained by theoretical models unless some finite propagation of a "pre-hadron" (with a smaller cross section than fully-formed hadrons) is assumed [5].

Here we present for the first time results for $K^0_s$ hadronization measured in SIDIS kinematics at CLAS. The $K^0_s$ was detected by reconstructing the invariant mass of a $\pi^+\pi^-$ pair from the $K^0_s$ decay branch. A sample mass spectrum showing the $K^0_s$ peak is shown in Fig. 2 for the Fe target in the energy fraction bin spanning $z = 0.5-0.6$. The number of $K^0_s$ particles was obtained by a gaussian fit over a smooth polynomial background. Similar fits were done for the liquid deuterium LD$_2$ target.

To get the multiplicity ratio, the number of $K^0_s$ events for SIDIS events were normalized by the number of DIS events with of $Q^2 > 1.0$ GeV$^2$ and $W > 2$ GeV. Unlike the CLAS $\pi^+$ hadronization data [4], the statistics for $K^0_s$ were not sufficient to obtain multiplicity ratios for different bins in $Q^2$ and $\nu$. Ratios of SIDIS/DIS were obtained for several targets (LD$_2$,C,Fe,Pb) and the multiplicity ratio $R$ was calculated for a given nuclear target normalized by the deuterium ratio. Small corrections for the detector efficiency from the difference in geometry of the nuclear and LD$_2$ targets were done with Monte Carlo simulations. Preliminary results are shown in Fig. 3 as a function of the energy fraction $z$ of the $K^0_s$.

Although the data in Fig. 3 are still preliminary, there is an indication that the multiplicity ratios are less attenuated (closer to unity) than for $\pi^+$ hadronization at the same kinematics. This in turn suggests that there is a dependence on the mass of the antiquark picked up by in the hadronization process of a meson, at least for $z > 0.5$ where the meson is likely to include the struck quark (and an antiquark from the breaking of the color flux tube).

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At the highest \( z \)-bin in Fig. 3, \( z = 0.7-0.8 \), the statistical uncertainties (shown by the error bars) are large, but there is a hint that the multiplicity ratio for carbon and iron targets diverges from the downward trend seen at lower \( z \). A similar effect was seen in the higher-statistics \( \pi^+ \) data above \( z = 0.8 \) shown in Fig. 1. The reason for this behavior in \( z \) is not known at the present time, however at the highest \( z \) the hadronization data are known to be dominated by quasifree resonance production at the CLAS kinematics. For the \( K^0 \) data (Fig. 3), the multiplicity ratio for \( z > 0.8 \) are not shown because quasifree resonance production is not the desired reaction mechanism in the calculation of \( R \).

Preliminary results of the average transverse momentum broadening, \( \Delta p_T^2 \), are shown in Fig. 4 for \( K^0 \) hadronization. Again, the statistical uncertainties are large, even after summing over the kinematics of the CLAS-eg2 experiment, but it appears that \( \Delta p_T^2 \) is broadened (greater than zero) as expected. The data in Fig. 4 show a hint of increased \( \Delta p_T^2 \) for larger nuclei \( A \), however the value for the three targets is consistent within error bars. For the higher-statistics \( \pi^+ \) data shown in Fig. 1, a clear dependence of \( \Delta p_T^2 \) is seen on the nuclear target.

As explained above, the value of \( \Delta p_T^2 \) is sensitive (in theoretical calculations) to gluonic radiation as the struck quark propagates through the nucleus, before forming a hadron. Comparison of the value of \( \Delta p_T^2 \) for different mesons (such as pions and kaons) are of interest to theorists. It is possible that the propagation time of the struck quark (before the breaking of the color flux tube) could be different depending on the mass of the antiquark in a given meson.

Clearly, higher statistics for \( K^0 \) hadronization are necessary before any conclusions can be drawn from theoretical interpretations of the \( \Delta p_T^2 \) data from CLAS-eg2. Partly for this reason, a proposal was approved to study hadronization at the planned upgrade to 12 GeV electron beam energy at Jefferson Lab [8]. The CLAS detector will also be upgraded to handle the higher-momentum particles from the 12 GeV beams, with particular emphasis on DIS kinematics with higher luminosity (up to \( 10^{35} \text{ cm}^{-2}\text{s}^{-1} \)). With this upgrade, a wider range of DIS kinematics will be accessible by CLAS12. At the higher beam energies, kaon production is known to have higher rates of production, allowing greater statistical accuracy.

3 Summary

In conclusion, the CLAS data provide a new kinematic window for hadronization at the expected length scale near to the radius of heavy nuclei. Statistical uncertainties for \( K^0 \) hadronization in DIS kinematics at CLAS-eg2 are still large, even though the CLAS-eg2 luminosity is larger than for the HERMES data by a factor of \( \sim 100 \), in part because of the low production rates for \( K^0 \) mesons at lower average \( \nu \). Nonetheless, the preliminary data shown here are the only available data for \( K^0 \) hadronization and hence are a first step.
toward extending the HERMES results. Both $\pi^+$ and $K^0_s$ multiplicity ratios and $\Delta p_T^2$ are expected to be finalized in the near future, as more data from the eg2 run becomes available.

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