1 Investigating in-medium hadronization and EMC effects by semi-inclusive deep inelastic scattering off nuclei

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Abstract

The semi-inclusive deep inelastic scattering of electrons off a nucleus A, with detection of a slow nucleus $(A-1)$, is shown to provide useful information on the mechanisms of hadronization and the origin of the EMC effect. The possibility to investigate such a process at the EIC is discussed.

The SIDIS process $A(e,e'(A-1))X$ in which, instead of the leading hadron, a nucleus $(A-1)$ in the ground or in low excitation states is detected in coincidence with the scattered electron, has been proposed [1] and investigated [2, 3, 4, 5], showing that it can provide

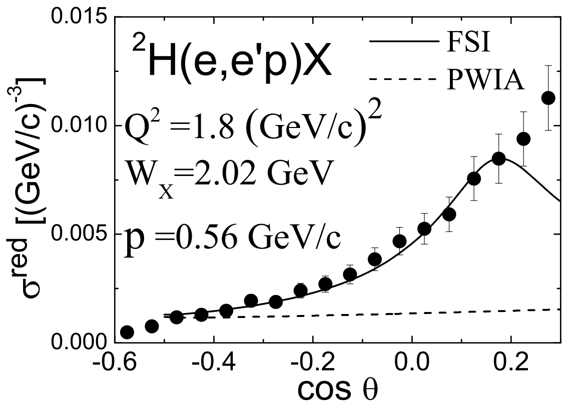

Figure 1: The Jlab experimental reduced cross section (the experimental cross section divided by the factor K^A in eq. (2)) [8] of the process $^2H(e,e'p)X$, *vs.* $cos\theta$ ($\theta = \theta_{\widehat{\mathbf{pq}}}$) compared with theoretical predictions [4]. Here W_X is the invariant mass of the hadronic state X, and $p = |\mathbf{p}|$ the momentum of the detected proton. The full curve includes the debris-nucleon final state interaction.

new information about the mechanism of hadronization and the origin of the EMC effect. The basic ingredients entering the process are: (i) the nuclear momentum distributions; (ii) the effective cross section of the interaction between the hadronizing nucleon debris and the spectator nucleons; (iii) the nucleon structure function in the medium. Two main advantages of the new SIDIS process over the classical SIDIS [6] and inclusive $A(e,e')X$ scattering are worth being mentioned. First, it can provide a new insight into the spacetime development of hadronization at the early stage. As a matter of fact, detecting a jet produced in a nucleus, information about its time development can be obtained, but in a rather complicated way, since cascading inside the nuclear medium essentially modifies the observables.

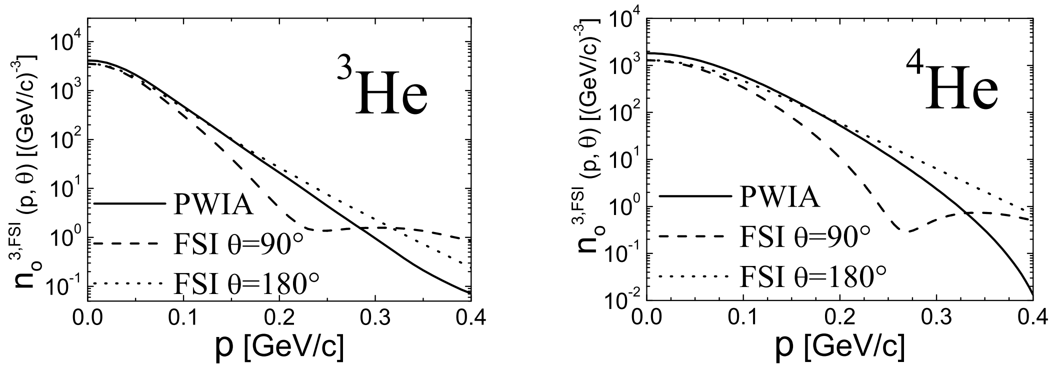

Figure 2: The distorted momentum distributions $n_0^{A,FSI}(\mathbf{P}_{A-1}) \equiv n_0^{A,FSI}(p,\theta)$ (eq. (3)) for ^3He and ^4He. *Full curves*: plane wave impulse approximation (PWIA) ($\sigma_{eff} = 0$); *dotted and dashed curves*: final state interaction ($\sigma_{eff} \neq 0$) in parallel ($\theta = 180^0$) and perpendicular ($\theta = 90^0$) kinematics (here, and in the following figures $p = |\mathbf{P}_{A-1}|$).

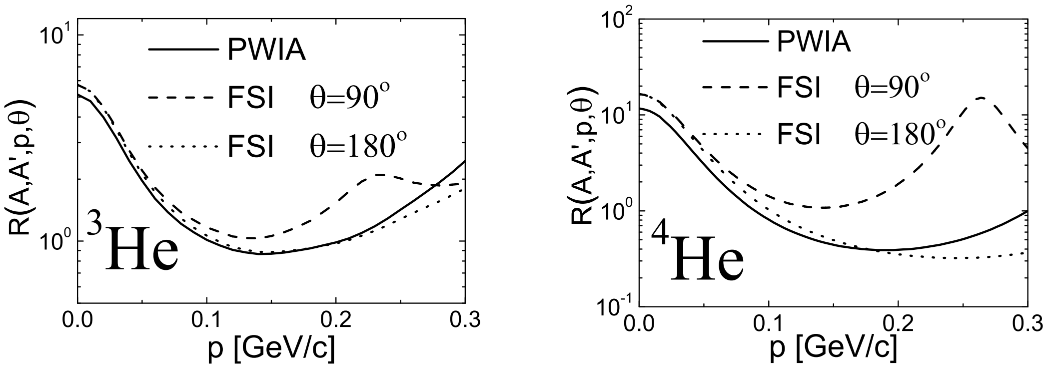

Figure 3: The ratio (4) with $A = 2$, $A' = 3$ and $A = 2$, $A' = 4$. *Full curve*: $\sigma_{eff} = 0$; *dotted and dashed curves*: $\sigma_{eff} \neq 0$, in parallel and perpendicular kinematics.

Measuring the recoil nucleus supplies additional and cleaner information about the dynamics of hadronization, for this process is free of the uncertainties caused by cascading, and the survival probability of the recoil nucleus is extremely sensitive to the multiparticle components of the jet [2]. Moreover (see below), a proper ratio of the cross sections on nucleus A taken at different values of the Bjorken scaling variable x_{Bj} provides information on the nucleon structure functions in the medium $F_2^{N/A}$. Several experimental projects to investigate the new process at 12 GeV Jlab have been proposed [7], and the experiment on a Deuteron target has already been performed [8]. The basic quantity entering the new SIDIS process is the final state interaction (FSI) of the hadronizing debris with the nucleons of $(A-1)$, which can be described by the effective debris-nucleon cross section of Ref. [2]

$$\sigma_{eff}(z, x_{Bj}, Q^2) \equiv \sigma_{eff}(z) = \sigma_{tot}^{NN} + \sigma_{tot}^{\pi N}\left[\, n_M(z) + n_G(z)\right], \qquad (1)$$

where σ_{tot}^{NN} and $\sigma_{tot}^{\pi N}$ are the total nucleon-nucleon (NN) and pion-nucleon (πN) cross sections and the Q^2- and x_{Bj}-dependent quantities $n_M(z)$ and $n_G(z)$ denote the pion multiplicities due to the breaking of the color string and to gluon radiation, respectively [9].

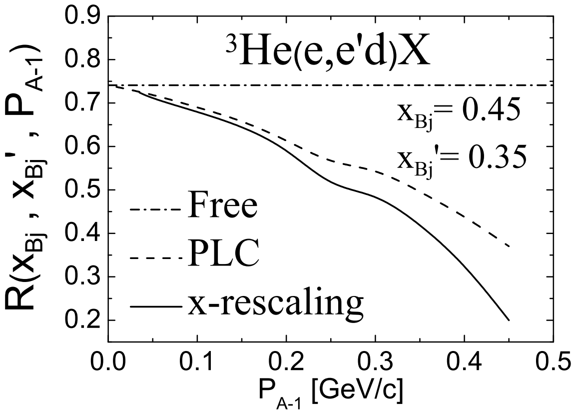

Figure 4: The ratio (5) corresponding to the process $^3He(e,e'd)X$ calculated [4] with different nucleon structure functions: i) free structure function (*dot-dashed line*); ii) off mass-shell (x-rescaling) structure function (*full line*); iii) structure function with reduction of point-like configurations (PLC) in the medium, depending upon the nucleon virtuality [10] (*dashed line*) ($P_{A-1} \equiv |\mathbf{P}_{A-1}|$).

The cross section of the process $A(e,e'(A-1))X$ reads as follows [2, 3]

$$\frac{d\sigma^{A,FSI}}{dx_{Bj}dQ^2 d\mathbf{P}_{A-1}} = K^A(x_{Bj}, Q^2, y_A, z_1^{(A)}) \left(\frac{y}{y^A}\right)^2 z_1^{(A)} F_2^{N/A}(x_A, Q^2, k_1^2)\, n_0^{A,FSI}(\mathbf{P}_{A-1}) \quad (2)$$

where K^A is a kinematical factor, $y_A = (k_1{\cdot}q)/(k_1{\cdot}k_e)$, $x_A = x_{Bj}/z_1^{(A)}$, $z_1^{(A)} = (k_1{\cdot}q)/(m_N\nu)$, and k_1 is the four-momentum of the bound nucleon. In eq. (2) $n_0^{A,FSI}(\mathbf{P}_{A-1})$ is the momentum distribution distorted by the debris-nucleon FSI

$$n_0^{A,FSI}(\mathbf{P}_{A-1}) = \frac{1}{2J_A+1} \sum_{\mathcal{M}_A,\mathcal{M}_{A-1}} \left| \int d\mathbf{r}_1' e^{i\mathbf{P}_{A-1}\mathbf{r}_1'} \langle \Psi^0_{J_{A-1},\mathcal{M}_{A-1}} | S_{FSI}^{XN} | \Psi^0_{J_A,\mathcal{M}_A} \rangle \right|^2, \quad (3)$$

where S_{FSI}^{XN} is the debris-nucleon eikonal scattering S-matrix which differs from the usual form by the presence of a z-dependent profile function generated by the z-dependent σ_{eff} (eq. (1)). Calculations of eq. (2) for Deuteron [4], ^3He [4], and ^4He [5], have been performed using few-body wave functions corresponding to the realistic NN interactions. In fig. 1, the Jlab experimental data on the process $^2H(e,e'p)X$ [8] are compared with parameter-free theoretical calculations [4]. The distorted momentum distributions of ^3He, calculated at appropriate EIC kinematics [4], and ^4He [5], are shown in fig. 2: it can be seen that the FSI, governed by the details of σ_{eff}, strongly affects the survival probability of $(A-1)$. Let us denote the cross section (2) by $\sigma^{A,FSI}$. Then, if our description is correct, the ratio

$$R(A, A', \mathbf{P}_{A-1}) = \frac{\sigma^{A,exp}(x_{Bj}, Q^2, |\mathbf{P}_{A-1}|, z_1^{(A)}, y_A)}{\sigma^{A',exp}(x_{Bj}, Q^2, |\mathbf{P}_{A-1}|, z_1^{(A')}, y_{A'})} \to \frac{n_0^{(A,FSI)}(\mathbf{P}_{A-1})}{n_0^{(A',FSI)}(\mathbf{P}_{A-1})} \quad (4)$$

should be governed only by the FSI, with a dependence upon $\mathbf{P}_{A-1}$ as shown in fig. 3. Moreover, it it has been demonstrated in [1] that the ratio

$$R(x_{Bj}, x'_{Bj}, |\mathbf{P}_{A-1}|) = \frac{\sigma^{A,exp}(x_{Bj}, Q^2, |\mathbf{P}_{A-1}|, z_1^{(A)}, y_A)}{\sigma^{A,exp}(x'_{Bj}, Q^2, |\mathbf{P}_{A-1}|, z_1^{(A)}, y_A)} \to \frac{F_2^{N/A}(x_A, Q^2, k_1^2)}{F_2^{N/A}(x'_A, Q^2, k_1^2)} \quad (5)$$

for a nucleus A, measured at two different values of x_{Bj}, is essentially governed only by the nucleon structure function $F_2^{N/A}$. Calculations of this ratio have been performed [4] using two different in-medium structure functions, yielding only a few percent difference in the inclusive cross section. It can be seen from fig. 4 that, at $P_{A-1} \equiv |\mathbf{P}_{A-1}| \geq 0.4$ GeV$/c$, the two structure functions may differ by about 40 % in the new SIDIS process.

From what exhibited here and in the original papers [1, 2, 3, 4, 5] it appears that the SIDIS process $A(e, e'(A-1))X$ would be extremely useful to clarify the origin of the EMC effect and to study the early stage of hadronization at short formation times. At EIC kinematics (large Q^2 and W_X^2) the theoretical assumptions underlying eqs. (1), (2), and (3), are expected to be of higher validity. We have calculated the process $^3He(e, e'd)X$ at various EIC kinematics and found that, e.g. at $Q^2 \simeq 30$ GeV^2 and $x_{Bj} \simeq 0.7$, when the Deuteron is emitted at about 90^0 in the target rest frame this corresponds to about 1^0 in the direction of the incident nucleus in the collider CM system.

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