Slow proton production in semi-inclusive DIS off nuclei: the role of final state interaction

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The effects of the final state interaction on the production of slow protons in semi-inclusive deep-inelastic lepton scattering off nuclei is considered within the spectator mechanism and a realistic approach in which the rescattering in the medium of both the recoiling proton and the hadronizing nucleon debris are taken into account.

1. Introduction

Semi inclusive Deep Inelastic Scattering (SIDIS) of leptons off nuclei can provide relevant information on: (i) possible modification of the nucleon structure function in medium (EMC-like effects), (ii) the relevance of exotic configurations at short NN distances; (iii) the mechanism of quark hadronization (see e.g. [1]). A process which attracted much interest from both the theoretical [2, 3] and experimental [4] points of view is the production of slow protons, i.e. the process A(l,l'p)X. In plane wave impulse approximation (PWIA), after the hard collision of $\gamma^*$ with a quark of a bound nucleon, two main mechanisms of production of slow protons have been considered; they are depicted in Figs. 1a and 1b and represent, respectively, the target fragmentation mechanism and the spectator mechanism. The latter occurs because of nucleon-nucleon (NN) correlations, namely $\gamma^*$ is absorbed by a nucleon of a correlated pair and the second nucleon (the spectator nucleon) is emitted by recoil and detected in coincidence with the scattered lepton [1]. The spectator mechanism has been intensively investigated (see e.g. [2, 3]), but most calculations either completely disregard the effects of the final state interaction, or considered them within simple models. In this contribution the first results of the calculation of the cross section for the spectator mechanism within a realistic approach for the treatment of the FSI are presented. A full account of our approach will be given elsewhere [5].

2. The spectator mechanism within the PWIA

In the Bjorken limit the PWIA cross section for the spectator mechanism is governed, apart from trivial kinematical factors, by the nuclear structure function

$$F_2^A(x, p_2) = \int_x^{M_A/m_N-z_2} dz_1 z_1 F_2^N\left(\frac{x}{z_1}\right) \int d\mathbf{k}_{cm} dE^{(2)} S(\mathbf{k}_{cm} - \mathbf{k}_2, \mathbf{k}_2, E^{(2)}) \times$$

$$\times \delta(M_A - m_N(z_1 + z_2) - M_{A-2}^f z_{A-2})$$

(1)
where the $z$-axis is directed along the momentum transfer $\mathbf{q}$, $\mathbf{k}_{cm} = \mathbf{k}_1 + \mathbf{k}_2 = -\mathbf{P}_{A-2}$, $F^N_2(x/z)$ is the structure function of the hit nucleon, $x = Q/(2m_N\nu)$ is the Bjorken scaling variable, $z_1 = k_1^+/m_N$, $z_2 = [(m_N^2 + \mathbf{p}_2^2)^{1/2} - |\mathbf{p}_2|\cos\theta_2]/m_N$, and $z_{A-2} = [((M^f_{A-2})^2 + \mathbf{k}_{cm}^2)^{1/2} + (\mathbf{k}_{cm}^2)/M^f_{A-2}]$ are the light-cone momenta of hit nucleon, the detected nucleon and the recoiling spectator nucleus $A-2$, respectively, and, eventually, $S(\mathbf{k}_1 = \mathbf{k}_{cm} - \mathbf{k}_2, \mathbf{k}_2, E^{(2)})$ is the two nucleon spectral function, with $E^{(2)}$ being the two nucleon removal energy.

Figure 1. Slow nucleon production in the process $A(e,e'p)X$ by target fragmentation (a) and by the spectator mechanism (b). The final state interaction in the spectator mechanism considered in our approach is depicted in (c).

Two model spectral functions have been considered in the literature: i) the two nucleon correlation (2NC) model [1], and ii) the extended 2NC model [6]. Both of them assume that the momentum and removal energy dependencies are only governed by the dynamics of a two nucleon correlated pair, with the $(A-2)$ nucleus acting as a spectator in the ground state. In the extended 2NC model the CM motion of the pair is taken into account and the spectral function has the form

$$S(\mathbf{k}_1, \mathbf{k}_2, E) = n_{rel}(|\mathbf{k}_1 - \mathbf{k}_2|/2) n_{cm}(|\mathbf{k}_1 + \mathbf{k}_2|) \delta(E - E^{(2)}_{th})$$

where $E^{(2)}_{th}$ is the two nucleon emission threshold. In the 2NC model the correlated pair is at rest, i.e. $n_{cm}(\mathbf{k}_{cm}) = \delta(\mathbf{k}_{cm})$; in this approximation, nuclear effects amount to a momentum-dependent rescaling of the argument of $F^N_2$, namely $F^N_2(x/z_1) \rightarrow F^N_2(x/\tau_1)$ with $\tau_1 \simeq 2 - z_2$ [1]; such a relation is modified by the CM motion of the pair [3]. In the present contribution we go beyond the PWIA and consider two different kinds of FSI: i) the one of the nucleon debris formed after $\gamma^*$ absorption, with the spectator $A-2$ system; ii) the one of the recoiling nucleon with $A-2$. Both processes, depicted in Fig. 1c, should strongly affect the survival probability of the the spectator $A-2$ and, consequently, the cross section of the process.
3. The final state interaction and the spectator mechanism

Using momentum conservation \( p_X = q - p_2 - P_{A-2} \), the transition matrix element of the process \( A(e,e'p)(A-2) \) is as follows

\[
T_{fi} \propto \int \prod_{i=1}^{A} d \mathbf{r}_i e^{i(\mathbf{P}_{A-2}+\mathbf{p}_2) \cdot \mathbf{r}_1} e^{-i\mathbf{p}_2 \cdot \mathbf{r}_2} \psi_f^{*} \mathbf{A}_{A-2} \hat{S}_{FSI} \psi_0^0. \tag{3}
\]

Here \( \hat{S}_{FSI} \) is the FSI operator, assumed to have the following form

\[
\hat{S}_{FSI}(\mathbf{r}_1, \mathbf{r}_2, \ldots, \mathbf{r}_A) = D_{p_2}(\mathbf{r}_2) \prod_{i=3}^{A} G(1,i) \tag{4}
\]

where \( D_{p_2} \) and \( \prod_{i=3}^{A} G(1,i) \) take into account the interaction with \( A-2 \) of the slow recoiling proton and the fast hit-nucleon-debris, respectively. The first is described by an eikonal wave distorted by a complex optical potential, viz

\[
D_{p_2}(\mathbf{r}_2) = \exp \left( i \frac{E}{p_2} \int_{z_2}^{\infty} dz V(x_2, y_2, z) \right) \tag{5}
\]

with the imaginary part of \( V(\mathbf{r}) \) reducing the proton flux. As for the interaction of the nucleon debris, following \[7\] we write \( G(1,i) = 1 - \theta(z_i - z_1) \Gamma(b_1 - b_i, z_i - z_1) \), with the \( z \)-dependent profile given by

\[
\Gamma(b_1 - b_i, z_i - z_1) = \frac{(1 - i\alpha) \sigma_{eff}(z_i - z_1)}{4 \pi b_0^2} \exp \left( -\frac{(b_1 - b_i)^2}{2b_0^2} \right) \tag{6}
\]

where the novel and main ingredient in our approach is the time-space-dependent debris-nucleon cross section which has the following form \( \sigma_{eff}(t) = \sigma_{tot}^{NN} + \sigma_{tot}^{NN} n_M(t) + n_G(t) \); here the first term describes the interaction of the baryon resulting from the initial hard \( \gamma^* \)-nucleon collision, whereas the second term represents the production of (pre)-hadrons (colorless \( q \bar{q} \) dipoles) by the string decay \( n_M(t) \) and by gluon radiation \( n_G(t) \). It has been shown in \[8\] that \( \sigma_{eff}(t) \) provides a nice description of grey track production in DIS off nuclei. The interaction between the debris and the recoiling nucleon, which has been shown to slightly affect backward nucleon emission at least in the process \( ^2H(e,e'p)X \) \[9\], will be treated elsewhere \[10\].

4. Results and conclusions

We have calculated the differential cross section for the process \( A(e,e'p)(A-2) \) for various nuclei within the PWIA and taking FSI into account \[5\]. For the sake of illustration of the effects of FSI, we show in Fig. 2 the results for the process \( ^{12}C(e,e'p)^{10}B \) with detection of the slow proton both in the forward \( (\theta_2 = 25^\circ, z_2 < 1) \) and backward \( (\theta_2 = 140^\circ, z_2 > 1) \) hemispheres (note that at \( x > 1 \) nucleons from the spectator mechanism can only be emitted forward). Two main conclusions are worth being mentioned: i) Backward emission, which can experimentally be accessed \[4\], is very sensitive to nuclear effects (the 2NC model exhibits kinematical restrictions which are not present in the extended 2NC
Figure 2. The DIS differential cross section for the process $^{12}\text{C}(e,e'p)X$ versus the kinetic energy $T_2$ of the detected proton, emitted forward at $\theta_2 = 25^0$ (left) and backward at $\theta_2 = 140^0$ (right), for various values of the Bjorken variable $x$. The dashed and full lines represent the results obtained within the extended 2NC model (PWIA) and the full FSI, respectively.

model; ii) FSI appreciably decrease the cross section, the largest effect arising from the rescattering of the produced (pre)-hadrons on the nucleon of the spectator $A - 2$ system. The approach we have developed will allow us to perform quantitative comparisons with available experimental data [4] and to provide a significant answer to the question as to whether reliable information on the structure function of bound nucleons and, possibly, on hadronization mechanisms could be obtained by means of SIDIS off complex nuclei with slow nucleon production.

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