SLOW PROTON PRODUCTION IN SEMI-INCLUSIVE DIS OFF NUCLEI

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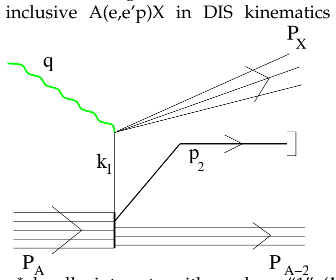
ABSTRACT

Deep Inelastic Scattering (DIS) of leptons off nuclei can provide relevant informations on the origin of nuclear forces and the short-range structure of hadronic matter [1], in particular on the mechanism of quark hadronization. Slow proton production is analyzed in semi-inclusive DIS process $A(e, e'p)X$ off nuclei within the spectator (or recoil) mechanism according to which, after lepton interaction with a quark of a nucleon belonging to a correlated pair, the spectator nucleon is emitted because of recoil and detected in coincidence with the scattered lepton [2]. Nuclear effects are investigated within the spectator mechanism and results of calculations are presented for forward and backward emissions at $x_{Bj} < 1$. The Final State Interaction, due to the propagation of the recoiling proton and of the struck nucleon debris , is considered. The effective cross-section of the nuclear debris with the nucleons of the medium is time-dependent and is estimated on the basis of a model which takes into account both the production of hadrons due to the breaking of the color string as well as the production of hadrons originating from gluon radiation [3, 4]. The FSI between the recoiling proton and residual (A-2) nucleus is investigated whitin the optical potential approach (DWIA) [6].

1 - PWIA

- Within PWIA, where any kind of FSI is disregarded, the mechanism leading to low-momentum proton emission in semi-inclusive A(e,e'p)X in DIS kinematics is described by the diagram:



$A-2$ nucleus recoil four-momentum P_{A-2}:

$$\left(\sqrt{(M^f_{A-2})^2 + \boldsymbol{P}^2_{A-2}}, \boldsymbol{P}_{A-2}\right)$$

with $\boldsymbol{P}_{A-2} = -(\boldsymbol{k}_1 + \boldsymbol{k}_2)$

γ^* hardly interacts with nucleon "1" ($\boldsymbol{k}_1$) ***correlated*** with nucleon "2" ($\boldsymbol{k}_1 \equiv \boldsymbol{p}_2$) which is emitted with momentum $\boldsymbol{p}_2$ and detected in coincidence with the scattered electron.

- The relative and center of mass momenta of the ***correlated pair*** are:

$$\boldsymbol{k}_{rel} = \frac{1}{2}(\boldsymbol{k}_1 - \boldsymbol{k}_2) \qquad e \qquad \boldsymbol{k}_{cm} = (\boldsymbol{k}_1 + \boldsymbol{k}_2).$$

- In the Bjorken limit the cross-section for the *spectator* process is as follows:

$$\frac{d\sigma^A}{dE'\, d\Omega'\, dT_2\, d\Omega_2} = K'_{rec}\, F_2^A(x_{Bj}, Q^2, \boldsymbol{p}_2)\,,$$

where $K'_{rec} = \frac{4\,\alpha^2\,E}{Q^4}\left(1 - y + \frac{y^2}{2}\right)\left(\frac{1-y}{y}\right)(T_2 + M)\sqrt{T_2^2 + 2MT_2}$ is a kinematical factor. The nuclear structure function is

$$F_2^A(x_{Bj}, Q^2, \boldsymbol{p}_2) = M \sum_{N_1=1}^{A} \int_{x_{Bj}}^{M_A/M - z_2} dz_1 z_1 F_2^{N_1}\left(\frac{x_{Bj}}{z_1}, Q^2\right) \times$$

$$\times \int d\boldsymbol{k}_{cm}\, dE\, P_{N_1 N_2}(\boldsymbol{k}_1 = \boldsymbol{k}_{cm} - \boldsymbol{p}_2, \boldsymbol{k}_2 = \boldsymbol{p}_2; E)\, \delta(M_A - M(z_1 + z_2) - M^f_{A-2} z_{A-2})\,,$$

where $P_{N_1 N_2}(\boldsymbol{k}_1, \boldsymbol{k}_2; E)$ is the two-nucleon spectral function.

1.1 - The extended *two nucleon correlation model* [6]

- In the *extended* *2NC model*, the spectral function can be written as follows:

$$P_{N_1 N_2}(\boldsymbol{k}_1, \boldsymbol{k}_2; E) = n_{rel}^{N_1 N_2}(|\boldsymbol{k}_1 - \boldsymbol{k}_2|/2)\, n_{cm}^{N_1 N_2}(\boldsymbol{k}_1 + \boldsymbol{k}_2)\, \delta(E - E_{thr})\,;$$

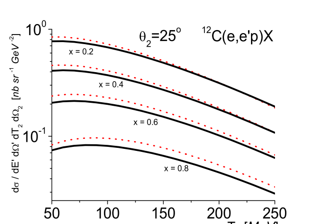
for the ^{12}C nucleus we used the following center of mass momentum distribution:

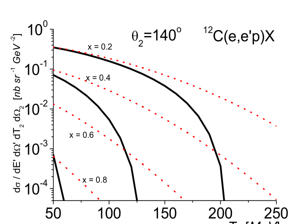
$$n_{cm}(|\boldsymbol{k}_{cm}|) = \left(\frac{\alpha_{cm}}{\pi}\right)^{3/2} e^{\alpha_{cm}\boldsymbol{k}^2_{cm}}\ ; \qquad \alpha_{cm} = 1 fm^2;$$

for the relative momentum distribution we properly rescaled the ^2H distribution:

$$n_{rel}(|\boldsymbol{k}_{rel}|) \sim C_A\, n_{^2H}(|\boldsymbol{k}|)\,, \quad C_A \sim 4\,.$$

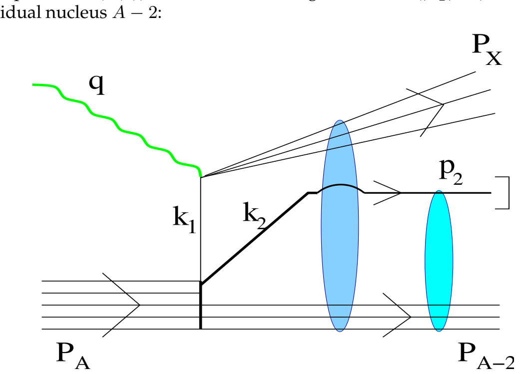
- We compare *extended* the **simple** two nucleon correlation model, which neglects the CM-motion, amounting to set $n_{cm}(|\boldsymbol{k}_{cm}|) \equiv \delta(|\boldsymbol{k}_{cm}|)$; the results are shown in the following figures for *forward* and *backward* kinematics:





2 - FSI: distorted spectral function

- We have calculated the interaction of the debris produced in the hadronization process ($\Gamma(\sigma(z))$) and of the recoiling nucleon ($D(|\boldsymbol{p}_2|, \boldsymbol{r}_2)$) with the residual nucleus $A-2$:



- The *distorted* spectral function reads as follows:

$$P^{\mathrm{D}}_{N_1 N_2}(\boldsymbol{P}_{A-2}, \boldsymbol{p}_2; E) = \sum_f |T_{fi}|^2 \delta(E - E_{thr})$$

T_{fi} is the transition matrix. From three-momentum conservation, $\boldsymbol{p}_X = \boldsymbol{q} - \boldsymbol{p}_2 - \boldsymbol{P}_{A-2}$, it follows that:

$$T_{fi} = \sum_f \left|\langle \boldsymbol{p}_X, \boldsymbol{p}_2, \Psi^f_{A-2}, \hat{S}_{FSI}|\boldsymbol{q}, \Psi^0_A\rangle\right|^2 =$$

$$= \int \prod_{i=1}^{A} d\boldsymbol{r}_i e^{i(\boldsymbol{P}_{A-2} + \boldsymbol{p}_2)\cdot\boldsymbol{r}_1} e^{-i\boldsymbol{p}_2\cdot\boldsymbol{r}_2} \Psi^{*f}_{A-2}(\boldsymbol{r}_3, \ldots \boldsymbol{r}_A) \hat{S}^+_{FSI}(\boldsymbol{r}_1, \ldots \boldsymbol{r}_A) \Psi^0_A(\boldsymbol{r}_1, \ldots \boldsymbol{r}_A)$$

in which $\hat{S}_{FSI}$ is the final state interaction operator:

$$\hat{S}_{FSI}(\boldsymbol{r}_1, \boldsymbol{r}_2, \ldots \boldsymbol{r}_A) = D_{p_2}(\boldsymbol{r}_2) \prod_{i=3}^{A} G(1, i).$$

2.1 - FSI: optical potential

- The interaction between the recoiling nucleon and the residual nucleus A-2 is described within an optical model approach: the outgoing nucleon plane wave becomes distorted as a consequence of the eikonal phase factor

$$e^{-i\boldsymbol{p}_2\cdot\boldsymbol{r}_2} \longrightarrow e^{-i\boldsymbol{p}_2\cdot\boldsymbol{r}_2} D_{p_2}(\boldsymbol{r}_2)\,,$$

where

$$D_{p_2}(\boldsymbol{r}_2) = exp\left(i\,\frac{E}{p_2}\int_{z_2}^{\infty} dz\, V(x_2, y_2, z_2)\right).$$

- The optical potential $V(x_2, y_2, z)$ does not depend on the individual coordinates of the spectator nucleons and embodies an effective description of how the nuclear medium influences the wave function of the propagating nucleon. We have a complex potential:

$$V(x, y, z) = (V_0 + iW_0)\, f(x, y, z)$$

in which the real part V_0 represents elastic re-scattering and the complex term absorption processes.

- the contribution to final state interactions of the spectator nucleon amounts to an attenuation factor which in the range of proton momentum $|\boldsymbol{p}_2|$ analyzed decreases the cross section by a factor of $\sim 0.5 - 0.7$, with a slight dependence on $|\boldsymbol{p}_2|$ itself.

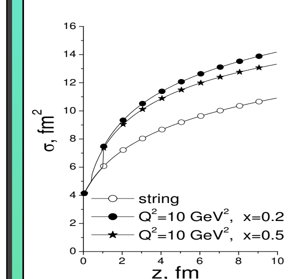
2.2 - FSI: Glauber Time-Dependent Approach

- The interaction between the struck nucleon debris and the residual nucleus A-2 is described within a Glauber approach, introducing the factor:

$$\prod_{i=3}^{A} G(1, i) = \prod_{i=3}^{A} (1 - \theta(z_i - z_1)\Gamma(\boldsymbol{b}_1 - \boldsymbol{b}_i, z_i - z_1))$$

$$\theta(z_i - z_1) \longrightarrow \textit{forward debris propagation and interaction}$$

$$\Gamma(\boldsymbol{b}_1 - \boldsymbol{b}_i, z_i - z_1) = \frac{(1 - i\alpha)\,\sigma_{eff}\,(z_i - z_1)}{4\pi\beta} e^{-(\boldsymbol{b}_1 - \boldsymbol{b}_i)^2/2\beta} \quad \textit{Profile Function}$$



$$t = z_i - z_1$$

$$\sigma_{eff} = \sigma^{NN}_{tot} + \sigma^{\pi N}_{tot}\left[n_M(t) + n_G(t)\right]$$

$$\sigma^{NN}_{tot} = 43mb\,; \qquad \sigma^{\pi N}_{tot} = 20mb$$

- $n_M(t) = \ln(1 + t/\Delta t)/\ln 2$
- $t_0 = 1/Mx$

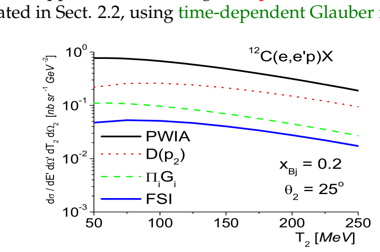
$$t < t_0 \qquad n_G(t) = \frac{16}{27}\left[\ln\frac{Q}{\lambda} + \ln\frac{\Lambda_{QCD}t}{2}\cdot\ln\left(\frac{\ln(Q/\Lambda_{QCD})}{\ln(\lambda/\Lambda_{QCD})}\right)\right]$$

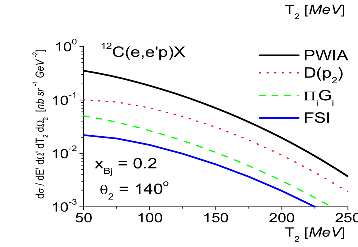
$$t_0 < t < \frac{Q^2}{\lambda^2}t_0 \qquad n_G(t) = \frac{16}{27}\left[\ln\frac{t_0 Q}{t\lambda} + \ln\frac{\Lambda_{QCD}t}{2}\cdot\ln\left(\frac{\ln(\sqrt{t_0/t}\cdot Q/\Lambda_{QCD})}{\ln(\lambda/\Lambda_{QCD})}\right) + \ln\frac{Q^2 t_0}{2\Lambda_{QCD}}\ln\left(\frac{\ln(Q/\Lambda_{QCD})}{\ln(\sqrt{t_0/t}\cdot Q/\Lambda_{QCD})}\right)\right]$$

$$t > \frac{Q^2}{\lambda^2}t_0 \qquad n_G(t) = \frac{16}{27}\left[\ln\frac{Q^2 t_0}{2\Lambda_{QCD}}\ln\left(\frac{\ln(Q/\Lambda_{QCD})}{\ln(\lambda/\Lambda_{QCD})}\right) - \ln\frac{Q}{\lambda}\right].$$

3 - RESULTS: separate contributions

- The effects of final state interaction have been first analyzed in two separate contributions: the first one, illustrated in Sect. 2.1, within a Distorted Wave Impulse Approximation, using the optical model , and the second one, illustrated in Sect. 2.2, using time-dependent Glauber model :

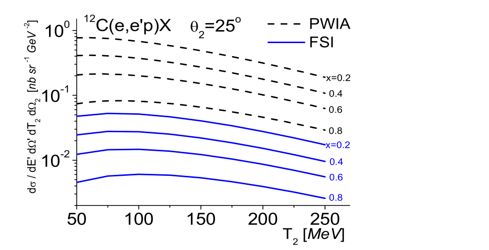


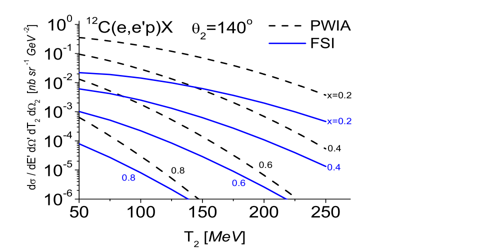


- The most relevant contribution to FSI is represented by hadronization of the hit quark, in forward as well as in backward nucleon emission.

3.1 - RESULTS: full FSI

- Final results for the $^{12}C(e, e'p)X$ differential cross section within the PWIA and with FSI described by the $\hat{S}_{FSI}$ operator of Sect. 2.





It is seen that, due to the presence of the recoil nucleon-$(A-2)$ interaction, the total effect of FSI is much stronger in the *forward* direction (*i.e.* $\theta_2 = 25^o$) than in the *backward* one ($\theta_2 = 140^o$).

CONCLUSIONS

- We have calculated the semi-inclusive reaction $^{12}C(e, e'p)X$ within the spectator mechanism, in the PWIA and with full FSI between the struck nucleon debris and the recoil proton (which is detected) and the residual $A-2$ nucleus
- The dependence of the cross section upon the kinetic energy T_2 of the detected nucleon is governed by the relative and CM momentum distribution of the correlated pair and by the structure function F_2 of the bound nucleon. It can be seen that backward nucleon emission is more sensitive to the two-nucleon spectral function: the center of mass motion cannot be neglected.
- The FSI has been modeled with a Glauber time-dependent approach, for the struck nucleon debris and $A-2$ nucleus interaction, and an optical potential interaction for the recoiling nucleon and the $A-2$ system
- The total effect of FSI amounts to a strong absorption of the emitted proton; the dominant effect of FSI for the calculated kinematics is due to the hadronization of the struck nucleon; the contribution of the FSI of the slow proton is less relevant.

References

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