Final state interaction in lepton scattering off deuterons

L.P. Kaptari

Bogoliubov Lab. Theor. Phys., JINR, 141980 Dubna, Russia

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The role of the final state interactions (FSI) in inclusive electro disintegration of the deuteron, $D(e, e')X$, is being investigated within different approaches. A detailed comparison between an improved Glauber method and the standard Schroedinger approach is presented. It is shown that both methods become inadequate at large values of $Q^2$, where the virtuality of the hit nucleon after photon absorption is very high. The concept of finite formation time (FFT) required by the hit hadron to reach its asymptotic form is introduced by a Feynman diagram approach and by explicitly taking into account the dependence of the ejected nucleon on its virtuality. The approach has been applied both at $x_{Bj} \approx 1$, as well as in the so called cumulative region i.e. at $x_{Bj} > 1$. Numerical calculations show that the effects of the FFT almost completely cancel the contribution from rescattering processes. In the cumulative region the color transparency or finite formation time effects become fairly visible.

Key Words:
Finite Formation Time, Color Transparency, Bethe-Salpeter, Final State Interaction.

I. INTRODUCTION

One of the most challenging aspects of the nowadays hadronic physics is the experimental and theoretical investigation of effects of Final State Interaction (FSI) in electromagnetic processes off nuclei at high energy and momentum transfers. As a matter of fact, these processes are viewed as a useful tool for studying several features of strong interactions at short distances and for checking the predictions of perturbative QCD. At high moment transfer,
when the electron probes extremely short distances, the strong interaction is expected to be screened in the same way as the atomic Coulomb field is screened at short distances in QED. In other words, in the quark-gluon debris, produced by the target quark which absorbed the highly virtual photon, the color forces are screened ("switched off") in the neighbourhood of the interaction spot. Only at a certain distance from the interaction point, known as the Formation or Hadronization Length (or, equivalently, the Finite Formation Time), the reaction products become able to interact. Moreover, the magnitude of the Hadronization Length strongly depends upon the kinematics of the process and, at least theoretically, there can exist situations when the strong interaction may completely vanish, a phenomenon known as Color Transparency (see for detail Refs. \[1, 2\] and references therein quoted). From the point of view of nuclear physics this means that after absorption of $\gamma^*$ the quark system is able to produce many physical states which, due to their coherent interaction in the final state, manifest a strong attenuation of the cross section with respect to the prediction of the usual eikonal theory. In the presence of CT, the ratio of the experimentally observed cross section to the one calculated theoretically within the Plane Wave Impulse Approximation (PWIA) is predicted to approach unity as $Q^2 \to \infty$. However, at finite $Q^2$ one should investigate the ratio of experimentally measured quantities to the ones computed taking into account the FSI effects; an observed deviation of such a ratio from unity, in agreement with the $Q^2$ dependence predicted by CT, would be unambiguous signal of the latter. Presently, evidence from the experimental study of proton production in $eA$ collisions seems to indicate that the CT effects are not yet visible up to $Q^2$ of the order $20 \text{GeV}^2/c^2$, which means that in this region the experimental data can satisfactorily be described within usual theoretical approaches. Since CT corrections are predicted to be small at finite $Q^2$, and because of the required theoretical difficulties in the treatment of FSI and CT effects, the choice of the processes and kinematics to be investigated, as well as of the theoretical frameworks for the interpretation of the data, is of great importance.

Another noteworthy aspect of FSI effects is its tight connection with the problem of the experimental investigation of Ground State Correlations (GSC) in nuclei, particularly those which originate from the $NN$-correlations at short distances. There is a renewed interest in this topic in view of new experimental possibilities in the investigation of electro disintegration of light nuclei in semi inclusive and exclusive reactions (about the present status of experimental and theoretical investigations of GSC in nuclei see, e.g., Ref \[3\]).
A detailed study of GSC would allow to obtain additional information about the nuclear wave function and to directly check the validity of the Standard Model of nuclei as systems of non relativistic nucleons interacting via known $NN$ forces. Unfortunately, contrary to elastic processes, these inelastic electromagnetic reactions are affected by several effects (Final State Interaction among the reaction products, Meson Exchange Currents effects etc.), which may mask the effects of GSC. Therefore one needs reliable methods of calculations of the FSI corrections in these processes as well. Besides, since the study of GSC at short distances requires probes with relatively high momentum transfer, the question of the role of relativistic corrections cannot be neglected in theoretical treatments of the mechanism of the electro disintegration of nuclei.

In this context, the problem of a reliable theoretical calculations of relativistic effects, FSI and FFT effects appears to be of a great interest. In the present talk a study of the mentioned effects in the inclusive process of electro disintegration of the deuteron $D(e, e'p)X$, is presented. Investigations of the semi inclusive reactions of the type $A(e, e'p)$ for deuterons and light nuclei is in progress and will be reported elsewhere [4].

II. KINEMATICS AND CROSS SECTION

![Diagram](image)

FIG. 1: The diagrams of quasi elastic electro disintegration of a nucleus $A$ within the PWIA (a) and taking into account the Final State Interaction (b).

The invariant cross section for the electro disintegration of the target $A$ into the final hadron system $H$, can be written in a general form as
\[ d\sigma = \frac{1}{4k_s p_A} |\mathcal{M}_{e+A \rightarrow e' + H}|^2 (2\pi)^4 \delta^{(4)} (k + p_A - k' - p_H) \frac{d\mathbf{k}'}{(2\pi)^3 2\mathcal{E}'} d\tau_H, \]  

where the square of the invariant matrix element \(|\mathcal{M}_{e+A \rightarrow e' + H}|^2\) in the one-photon-exchange approximation can be written as

\[ |\mathcal{M}_{e+A \rightarrow e' + H}|^2 (2\pi)^4 \delta^{(4)} ((p_1 + q)^2 - m^2) = \frac{e^4}{Q^4} L^{\mu\nu}(k, q) W^A_{\mu\nu}(p_A, q), \]

with the known electromagnetic leptonic tensor \(L^{\mu\nu}(k, q)\), \(L^{\mu\nu}(k, q) = 2 \left( 2k_\mu k_\nu - (k_\mu q_\nu + k_\nu q_\mu) + g_{\mu\nu} q^2 \right)\). The (generally unknown) hadronic tensor \(W^A_{\mu\nu}\) besides electromagnetic interaction also involves information about the strong structure of the interaction currents. So, in case of elastic electron scattering from nucleons the electromagnetic nucleon vertex \(\Gamma^{eN}_\mu(Q^2)\) is usually parametrized in terms of two elastic form factors

\[ \Gamma^{eN}_\mu(Q^2) = \gamma_\mu F_1(Q^2) + i \frac{\mathbf{\sigma}_{\mu\nu} q^\nu}{2m} \kappa F_2(Q^2), \]

with the resulting tensor \(W^{eN}_{\mu\nu}\)

\[ W^{eN}_{\mu\nu}(p_1, q) = \frac{1}{2} \text{Tr} \left\{ (\hat{p}_1 + m) \Gamma^{eN}_\mu(Q^2)(\hat{p}_1 + \hat{q} + m) \Gamma^{eN}_\nu(Q^2) \right\} (2\pi)^4 \delta \left( (p_1 + q)^2 - m^2 \right), \]

which being contracted with the leptonic tensor provides the well known Rosenbluth formula for the cross section.

In the case of a complex system the form of the hadronic tensor cannot be unambiguously defined and some theoretical models have to be used to relate the nuclear tensor via the known nucleon one. In what follows, for the sake of simplicity we concentrate attention on the simplest nucleus, the deuteron. However, all results and conclusions hold for complex nuclei as well.

**A. PWIA**

The simplest theoretical approach to calculate the hadronic tensor is the plane wave impulse approximation (PWIA) which assumes that i) the nuclear electromagnetic current is a sum of solely one-nucleon currents ii) the final state interaction between the struck nucleon and the residual nucleus does not contribute to the cross section (see fig. [1a]).
neglect of FSI implies that the state vector describing the final system can be presented as a tensor product of the corresponding vectors of the struck nucleon and the residual nucleus. This immediately allows to separately compute the matrix elements of nucleon currents and the part describing the nuclear $A-1$ structure. A direct calculation of the diagram on fig.1a (in both non relativistic \cite{5} and relativistic \cite{6}) approaches leads to the following form of the inclusive cross section

\[
\left( \frac{d\sigma}{d\mathcal{E}'d\Omega_{k'}} \right)_{PWIA}^{\text{eD}} = (2\pi) \int_{p_{\text{min}}}^{p_{\text{max}}} |p| d|p| n^D(|p|) \frac{E_{\vec{p}+\vec{q}}}{|\vec{q}|} (\sigma_{ep} + \sigma_{en}),
\]

where $(\sigma_{ep} + \sigma_{en})$ represents the cross section of electron scattering from an isoscalar nucleon; the quantity $n_D$ in the non relativistic limit is the familiar deuteron momentum distribution related with the deuteron wave function as follows

\[
n^D(|p|) = \frac{1}{3(2\pi)^3} \sum_{M_D} \left| \int \Psi_{1,M_D}(r) \exp(i|p| r) dr \right|^2.
\]

FIG. 2: The deuteron momentum distribution computed within the covariant Bethe-Salpeter formalism (solid line) in comparison with non relativistic calculations with realistic NN-interactions, the Paris-group (dashed line) and Reid Soft Core (dotted line) potentials. The relativistic corrections from the P-waves in the deuteron are represented by the dash-dotted line (cf. Ref.\cite{6}).

In the relativistic case an analogue of the momentum distribution can be introduced as well, and in terms of the Bethe-Salpeter partial amplitudes reads as \cite{6}

\[
n^{\text{BS}}_D(p_0,|p|) = \left( \Psi^2_S(p_0,|p|) + \Psi^2_D(p_0,|p|) \right) + \frac{|p|}{E_p} \delta N(p_0, p),
\]

(7)
where the contribution from pure relativistic corrections ("negative" P-waves) is

$$\delta n(p_0, p) = \left\{ \frac{2\sqrt{3}}{3} \left[ \Psi_S(p_0, |p|) \left( \Psi_P^1(p_0, |p|) - \sqrt{2} \Psi_P^3(p_0, |p|) \right) + \Psi_D(p_0, |p|) \left( \sqrt{2} \Psi_P^1(p_0, |p|) + \Psi_P^3(p_0, |p|) \right) \right] \right\} \cdot (8)$$

Now the problem of whether the relativistic corrections play a role in the considered processes reduces to a comparison of the momentum distributions, computed within relativistic and the non relativistic approaches. In Fig. 2 the non relativistic deuteron momentum distribution predicted by realistic potentials (RSC and Paris-group) are compared with the ones obtained within the covariant BS formalism with a realistic one-boson-exchange kernel [7]. It can be seen that the relativistic corrections (8) are negligibly small so that in the kinematical region of our interests the two approaches provide basically identical results. Thus one can conclude that relativistic correction are irrelevant in the considered kinematical region and, for the sake of simplicity, all further analysis can be safely performed within the non relativistic limit. It is also worth emphasizing that corrections like relativistic meson exchange currents can be neglected as well, for in the covariant BS calculations of the momentum distribution the $N\bar{N}$- pair production is already taken into account within the PWIA [8].

III. THE RESCATTERING CONTRIBUTION

A. The Schroedinger Approach

At moderate momentum transfer $Q^2$ the total energy of the ejectile and the $A-1$ system can be relatively small, below the pion production threshold. In this case the most reliable method to take into account the FSI effects is to use the solution of the Schroedinger equation in the continuum for the final system. The corresponding cross section for the longitudinal current is [3]

$$\frac{d^3\sigma_L}{dQ'dE'} = \frac{4 M^2}{3} \frac{\sigma_{Mot}}{2\pi} V_L G_E(Q^2)^2 \sum_{J_f} \sum_{\lambda} \left| \langle J_D || \hat{O}_{\lambda} || p_{rel}; J_f L_f S_f \rangle \right|^2 \frac{|p_{rel}|}{\sqrt{s}} \cdot (9)$$

where $p_{rel}$ is the relative momentum of the $np$-pair which is defined by the Mandelstam variable $s = 4 (p_{rel}^2 + M^2)$; $\hat{O}_{\lambda\mu} = i^\lambda j_{\lambda}(qr/2)Y_{\lambda\mu}(\hat{r})$ and the scattering state $|p_{rel}; J_f L_f S_f \rangle$ describes the interaction of the two nucleons in the continuum.
It can be seen that equation (9) differs from the PWIA result (5). However, by using the identity
\[ \frac{1}{2|q|} \int_{|y|}^{p_{\text{max}}} |p| |d|p| E = \frac{p_{\text{rel}}}{\sqrt{s}} \]
one may cast the cross section in the form of eq. (5) by formally replacing the momentum distribution \( n_D(|p|) \) with the quantity \( n_D^S(|p|, |q|, \nu) \),

\[ n_D^S(|p|, |q|, \nu) = \frac{1}{4\pi} \frac{1}{3} \sum_{J_f} \sum_{\lambda} |\langle J_D | \hat{O}_\lambda(|q|) |p_{\text{rel}}; J_f L_f S_f \rangle|^2, \tag{10} \]

which can be called the distorted momentum distribution within the Schrödinger approach.

Note, that in absence of FSI, the state vector \( |p_{\text{rel}}; J_f L_f S_f \rangle \) is nothing but the multipole decomposition of the \( np \) plane wave and eq. (10) coincides exactly with the usual PWIA momentum distribution, eq. (6).

### B. The Glauber Approach

In the Glauber approach the exact two-nucleon continuum wave function \(|f>\) is approximated by its eikonal form. Then the cross section can be written in the same form as equation (9) with the deuteron momentum distribution (8) replaced by the Glauber distorted momentum distribution \( n_G^D \),

\[ n_D^G(p_m) = \frac{1}{3} \sum_{\mathcal{M}_D} \int dr \Psi_{1,\mathcal{M}_D}^* (r) S(r) \chi_f \exp(-i\mathbf{p}_m \mathbf{r}) \right|^2, \tag{11} \]

where \( \mathbf{p}_m = \mathbf{q} - \mathbf{p}_1 \) is the missing momentum, \( \chi_f \) the spin wave function of the final \( np \)-pair and \( S(r) \) the \( S \)-matrix describing the final state interaction between the hit nucleon and the spectator,

\[ S(r) = 1 - \theta(z) \Gamma_{el}(\mathbf{b}), \tag{12} \]

where \( \Gamma_{el}(\mathbf{b}) \) is the elastic profile function, \( \Gamma_{el}(\mathbf{b}) = \frac{\sigma_{tot}(1 - i\alpha)}{4\pi b_0^2} \exp(-b^2/2b_0^2) \), and \( \mathbf{r} = \mathbf{b} + z \mathbf{q}/|q| \) defines the longitudinal, \( z \), and the perpendicular, \( \mathbf{b} \), components of the relative coordinate \( \mathbf{r} \), \( \sigma_{tot} = \sigma_{el} + \sigma_{in} \), \( \alpha \) is the ratio of the real to the imaginary part of the forward elastic \( pn \) scattering amplitude, and, eventually, the step function \( \theta(z) \) originates from the Glauber’s high energy approximation, according to which the struck nucleon propagates along a straight-line trajectory and can interact with the spectator only provided \( z > 0 \).

It should be stressed, first, that in absence of any FSI, the distorted momentum distribution \( n_G^D(p_m) \) reduces to the undistorted momentum distribution \( n_G^D(p) \) \( (p_m = -p_1) \) and, secondly, that unlike \( n_D^G(p_m) \), \( n_G^D(p_m) \) depends also upon the orientation of \( p_m \) with respect...
FIG. 3: The scaling function $F(|q|, y)$ as a function of $|q|$ at two values of $|y| = p_{\text{min}}$, eq. (8). Dotted lines - PWIA. Dashed lines - FSI taken into account by the Schroedinger approach; full lines - FSI taken into account by the Glauber approximation (c.f. Ref. [5]).

to the momentum transfer $q$, with the angle $\theta_{q \dot{p}_m}$ being fixed by the energy conserving $\delta$-function, namely $\cos \theta_{q \dot{p}_m} = [(2(M_D + \nu)\sqrt{|\dot{p}_m|^2 + M^2 - s})/(2|q||\dot{p}_m|)];$ thus $n^D_D(p_m)$ depends implicitly on the kinematics of the process, and the values of $p_{\text{min}}$ and $|q|$ fix the value of the total energy of the final $np$ pair, i.e. the relative energy of the nucleons in the final states. Consequently, the quantities $\sigma_{\text{tot}}, \alpha$ and $b_0$ in also depend upon the kinematics of the process. In this sense, the distorted momentum distribution $n^D_D(p_m)$ implicitly depends upon $|q|$ and $p_{\text{min}}$ as well.

C. Schroedinger vs Glauber: numerical results

A formal comparative analysis of FSI effects can be performed by comparing the corresponding momentum distributions eqs. (10), (11) with the PWIA results, eq. (6). However such a direct comparison may not be quite enlightening, for in the considered processes besides the momentum distribution, $n^P$, the cross section is also determined by other kinematical factors and restrictions, which can strongly influence the magnitude of FSI effects. For this reason it is more convenient to present the results of calculation in terms of the scaling function $F(q, y)$, which is obtained from the cross section by eliminating all the irrelevant kinematical factors. In Fig. 3 the PWIA (dotted curves) is compared with the results which include FSI effects within the Schroedinger approach (dashed curves) and the
Glauber approximation (solid curves). The quantity $|y| = p_{\text{min}}$, eq. (5), determines which part of the intrinsic nucleon momenta contributes to the cross section. At low total energies $\sqrt{s}$ of the $np$ pair ($s = 2m^2 + 2m\sqrt{m^2 + p_{\text{lab}}^2}$) the Schroedinger approach provides a rather good description of the data, while the Glauber approximation is not valid at such relative energies. With increasing momentum transfer, the FSI contribution, computed within both approaches, decreases. Note that above the pion production threshold the use of the Schroedinger approach becomes questionable. Note also that, as seen from fig.3, at high momentum transfer the FSI corrections computed within the Glauber approximation remain almost constant.

**IV. FINITE FORMATION TIME**

As illustrated in the previous section, there is only a limited interval of momentum transfer $Q^2$ where the Glauber approximation holds: at low relative energy of the interacting $NN$ pair the use of the eikonal approximation is not justified, whereas at very high $Q^2$ the energy transfer may be too large to consider the struck nucleon as a real one. In this case, after the absorption of the virtual photon, the hadron state can be viewed as a superposition of many coherently interacting states. Obviously, this interaction can lead to a strong cancellation of the amplitudes and, as a result, one can expect a strong dilution of the FSI effects. Moreover, one may expect that while the usual nuclear shadowing, predicted by the eikonal approach, becomes almost $Q^2$-independent as $Q^2$ increases, the suppression of the FSI effects due to coherent interaction of many intermediate hadronic states should increase with increasing $Q^2$, leading asymptotically to the vanishing FSI effects.

The propagation of the hadronic debris in the residual nucleus can be taken into account by various effective theoretical models. At large values of the three-momentum transfer, one can modify the Glauber approach by adding another channel with an excited, effective hadronic state propagating through the nucleus, the two-channels generalization of the Glauber theory (see, e.g. [9]). Another possibility is to compute directly the Feynman diagram on fig.1 bearing in mind that in the intermediate state the propagator of the hit nucleon in the loop integration can be very far off mass-shell so that the secondary interaction of highly virtual nucleons (the second blob in the diagram, fig.1b) cannot be approximated by the real $NN$ scattering amplitude. It is known that the cross section of scattering of virtual particles
should decrease with increasing virtuality. This is equivalent to the known fact that after a particle has undergone an interaction, it should elapse a finite amount of time before it can be ready for a new one. During this time the virtual particle propagates without any interaction. Theoretically this can be taken into account by introducing suppressing form factors at each end of the nucleon line in the corresponding Feynman diagram, which formally consists in changing the ejectile propagators [10]:

$$\frac{1}{m^2 - (p + Q)^2} \rightarrow \frac{1}{m^2 - (p + Q)^2} - \frac{1}{m^* \cdot (p + Q)^2}$$

where the subtracted term may be considered as an effective contribution from the excited ejectile states, which makes the rescattering contribution to vanish at superhigh energies.

FIG. 4: The cross section (left panel) and scaling function (right panel) for the quasi-elastic $D(e, e')X$-reactions. The short-dashed lines represent the results of calculations within the PWIA; the dashed curves correspond to the Glauber approximation; the solid curves are the results which include rescattering and Finite Formation Time effects.

With the assumption (13) the rescattering contribution (Fig. 1) has been calculated within the assumptions of spinless active nucleon, i.e. the electromagnetic vertex (3) has been considered to depend only on one elastic form factor, which can be justified by the fact that in the ratios of relative contributions of rescattering terms to the PWIA amplitudes, uncertainties arising from neglecting the spin dependence of electromagnetic vertices are
expected to be significantly reduced and one may be able to reliable estimate the contribution of FFT corrections in the total cross section. Notice, that in general, the computation of Feynman diagrams with rescattering effects (fig. 1b) produces extremely lengthy and cumbersome expressions and even in the simplest case, the deuteron target, a compact analytical form of results is not feasible. However, at high enough $Q^2$ and at $x_{Bj} \sim 1$ one may drastically simplify the results and finally to represent the amplitude in an exactly eikonal form by formally replacing the $\theta(z)$ function in (12) with

$$\theta(z) \to \theta(z) \left[ 1 - \exp \left(-i\frac{z}{l(Q^2)}\right) \right],$$

(14)

where $l(Q^2) = \frac{Q^2}{x_{Bj}mm^2}$ is the formation length. As expected, the formation length increases with $Q^2$ and, as seen from eq. (14), at $Q^2 \to \infty$ it completely cancels the contribution from the usual eikonal rescattering term. Note that the result (14) holds not only for the deuteron target, but it is a more general result valid for any nuclear target, provided the multiple rescattering terms are much smaller than the single rescattering contribution. At $x_{Bj} \sim 1$ the inclusive quasi elastic reaction $D(e, e')X$ has been studied in Ref. [10], whereas recently [4] the theoretical approach has been extended to the so-called cumulative region ($x_{Bj} > 1$) where calculations, due to the effects of GSC, which provide high momentum components, are much more involved. The results are presented in Fig.4. It can be seen that at moderate values of the momentum transfer FSI effects are visible and, generally, improve the description of the cross section (the PWIA, dotted curves in Fig.4, are to be compared with rescattering contribution, dashed curves, and FFT effects, the full lines). At $Q^2 \to \infty$, as expected, FFT effects cancel the effects of elastic rescattering and the results are close to the PWIA predictions (see the right panel in fig.4). Unfortunately, present experimental data are far from the asymptotic region.

V. CONCLUSIONS

1. In the kinematical region of interest ($y < -0.8 GeV/c$, $s$-below the pion production threshold) the relativistic corrections (P-waves) may be disregarded and a covariant, relativistic momentum distribution in the deuteron may be defined which resembles the non relativistic distribution.
2. FSI corrections in inclusive electro disintegration of the deuteron may be reliably estimated in a large kinematical region of $Q^2$ and $\nu$ by the Schroedinger, Glauber and FFT approaches.

3. FFT effects play an important role in the considered reactions and, at high enough $Q^2$, they lead to an almost total cancellation of the rescattering corrections predicted by the one channel Glauber approximation.

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