Nearthreshold Large Q^2 Electroproduction off Polarized Deuteron

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Abstract: The exclusive and inclusive electroproduction off the polarized deuteron is considered at large Q^2 and $x \geq 0.5$. It is shown that the use of a polarized target will allow to emphasize smaller than average internucleon distances in the deuteron. As a result, we expect amplification of all the effects (color transparency, relativistic dynamics, etc.) sensitive to small internucleon distances. Numerical estimates are given for the processes $e + \vec{d} \to e + p + n$ and $e + \vec{d} \to e + X$.

1 Motivation

The theoretical analysis [1] of the intermediate energy $Q^2 \sim 1$ GeV^2 electrodisintegration of the deuteron at $x \sim 1$ indicates that there is a fast convergence of the higher (large l) partial waves of the final pn continuum wave function. As a result, we can substitute the (infinite) sum over the partial waves with the phenomenological amplitude for pn scattering. This simplification allows to implement relativistic kinematics of the final state interaction (FSI) amplitude through the analysis of the corresponding (covariant) Feynman diagrams [2]. The main theoretical conclusion [2] is that, at $Q^2 \geq 1$ GeV^2, there exists a unique scheme of legitimate calculations within the extended eikonal approximation which selfconsistently accounts for relativistic dynamics. This enhances considerably the exploration potential of the electroproduction reaction, especially off a deuteron target, whose wave function is well established at Fermi momenta ≤ 400 MeV/c.

Based on this, we discuss two alternative studies:

• Investigation of the QCD prediction that the absorption of a high momentum virtual photon by a nucleon leads to the production of a small size color singlet state, optimistically called a point-like configuration (PLC). Such a study requires selection of kinematics where small enough Fermi momenta dominate and where the transverse momenta of the spectator nucleons are large enough so that the dominant contribution is given by the reinteraction of the PLC with a spectator nucleon (see Sect. 2).

• Probing relativistic effects in deuteron electrodisintegration at moderate $Q^2 \leq 4$ GeV^2 and rather large longitudinal Fermi momenta. Such a study will provide a critical discrimination between the different approaches to high energy scattering off deeply bound nucleons.

Both these studies would greatly benefit from the use of a polarized target. The reason is that the use of a $\vec{d}$ allows to enhance the contribution of the D-state in the deuteron's ground state wave function. Due to the diminishing probability of the D-state at small Fermi momenta, these reactions would be sensitive to smaller internucleon distances in the deuteron as compared to the unpolarized case, leading to an amplification of all the effects sensitive to small internucleon distances.

2 Color Transparency Effects and Vanishing FSI

In QCD, the absorption of a high Q^2 photon by a nucleon produces a PLC, which, at very high energies, would not interact with the nucleons, thus eliminating FSI. This vanishing of

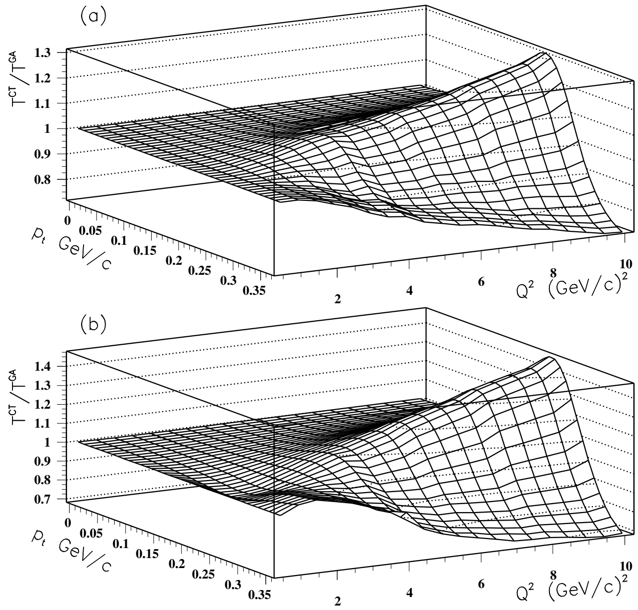

Figure 1: *p_t and Q^2 dependence of the ratio T^{GA}/T^{CT} for $\alpha \equiv (E_s - p_s^z)/m = 1$. a) quantum diffusion, b) three state model.*

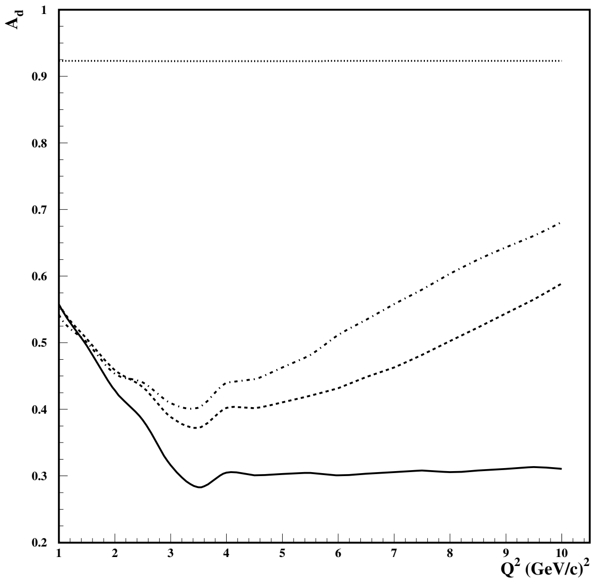

Figure 2: *Q^2 dependence of A_d for $\alpha = 1$. Solid line - elastic eikonal, dashed - QDM, dashed-dotted - three state model, dotted - PWIA.*

the FSI has been termed color transparency (CT). At high but finite energies, a PLC is actually produced, but it expands as it propagates through the nucleus [3]. To suppress the expansion effects, it is necessary to ensure that the expansion length, $l_h \sim 0.4(p/\mathrm{GeV})$, is greater than the characteristic longitudinal distance in the reaction. In the considered $d(e, e'pn)$ and $d(e, e'pN^*)$ reactions, where one nucleon carries almost all the momentum of the photon while the second nucleon (or its resonance) is a spectator, the actual expansion distances are the distances between the nucleons in the deuteron [1]. Thus, suppressing large distance effects through the deuteron's polarization, one effectively will diminish the PLC's expansion, leading to an earlier onset of CT.

The scattering amplitude $\mathcal{M}$, including the np final state interaction, can be written as:

$$\mathcal{M} =< p_s^z, \vec{p}_t|d> -\frac{1}{4i}\int \frac{d^2k_t}{(2\pi)^2} < \tilde{p}_s^z, \vec{p}_t - \vec{k}_t|d> \mathbf{F^{np}}(\vec{\mathbf{k}})\,[1-i\beta]\,, \tag{1}$$

where $\tilde{p}_s^z = p_s^z - (E_s - m)\frac{M_d+\nu}{|\vec{q}|}$ and $E_s = \sqrt{p_s^2 + m^2}$. Here, p_s is the spectator momentum and M_d the mass of the deuteron. The difference between $\tilde{p}_s^z$ and p_z accounts for the longitudinal momentum transfer. Spin indices are suppressed to simplify the notations. The function $\mathbf{F^{np}}$ represents the FSI between the outgoing baryons and its form depends on the model describing the soft rescattering. Within the elastic eikonal (Glauber) approximation (GA), $\mathbf{F^{np}}(\vec{\mathbf{k}}) \to f^{np}(\vec{\mathbf{k}}_\mathbf{t})$, where $f^{pn} = \sigma_{tot}^{pn}(i + a_n)e^{-b_n k_t^2/2}$. At $\mathrm{Q}^2 > 3$ (GeV/c)^2, the quantities σ_{tot}^{pn}, a_n and b_n depend only weakly on the momentum of the knocked-out nucleon, with $\sigma_{tot}^{pn} \approx 40$ mb, $a_n \approx -0.2$ and $b_n \approx\ 6-8$ GeV^{-2} for the kinematics we use.

The reduced interaction between the PLC and the spectator nucleon can be described in terms of its transverse size and the distance z from the photon absorption point, i.e., in Eq.(1) we replace $\mathbf{F^{pn}} \to f^{PLC,N}(z, k_t, Q^2)$. For numerical estimates of the reduced FSI $f^{PLC,N}(z, k_t, Q^2)$, we use the quantum diffusion model (QDM) [4] as well as the three state model [5]. Latter is based on the assumption that the hard scattering operator acts on a nucleon and produces a PLC, which is represented as a superposition of three baryonic states, $|PLC\rangle = \sum_{m=N,N^*,N^{**}} F_{m,N}(Q^2)|m\rangle$. In Fig.1, we compare the predictions of the elastic eikonal and the two CT models for the transparency, $T = \sigma^{FSI}_{e,e'p}/\sigma^{PWIA}_{e,e'p}$, for an unpolarized target. We consider so-called perpendicular kinematics, where the light cone momentum $\alpha = \frac{E_s - p^s_s}{m} \approx 1$ and $p_t \leq 400\ MeV/c$. It was demonstrated in Ref.[1] that these kinematics maximize the contribution from the FSI and minimizes various theoretical uncertainties. One can see from Fig.1 that, optimistically, one may expect 30% effects from CT at $Q^2 \geq 4-6$ GeV^2.

Using a polarized target emphasizes the role of the deuteron's D-state, allowing to probe the space-time evolution at smaller space-time intervals. For numerical estimates, we consider the asymmetry A_d measurable in electrodisintegration of a polarized deuteron with helcities of ±1 and 0: $A_d(Q^2,\vec{p}_s) = \frac{\sigma(1)+\sigma(-1)-2\cdot\sigma(0)}{\sigma(1)+\sigma(0)+\sigma(-1)}$, where $\sigma(s_z) \equiv \frac{d\sigma^{\vec{s},s_z}}{dE_{e'}d\Omega_{e'}d^3p}$ and s_z is the deuteron's helicity. The Q^2 dependence of the asymmetry A_d for "perpendicular" kinematics, at $p_t = 300$ MeV/c, is presented in Fig.2. One can see from this figure that CT effects can change A_d by as much as factor of two for $Q^2 \sim 10$ GeV^2.

3 Study of the Relativistic Effects

Let us consider now different kinematics, namely $Q^2 \leq 4$ GeV^2. In this case we expect minimal CT effects and therefore the consequences of the FSI are well under control. The kinematics, where the light-cone momentum $\alpha > 1$ and $p_t \approx 0$, are most sensitive to relativistic effects in the deuteron. There are several techniques to treat the deeply bound nucleons as well as relativistic effects in the deuteron. One group of approaches handles the virtuality of the bound nucleon within a description of the deuteron in the lab. frame (we will call them virtual nucleon (VN) approaches) by taking the residue over the energy of the spectator nucleon. One has to deal with negative energy states which arise for non-zero virtualities (see e.g. Ref.[6]). Due to the binding, current conservation is not automatic and one has to introduce a prescription to implement e.m. gauge invariance (see e.g. Ref.[7]). Another approach is based on the observation that high energy processes evolve along the light-cone. Therefore, it is natural to describe the reaction within the light-cone non-covariant framework [8]. Negative energy states do not enter in this case, though one has to take into account so called instantaneous interactions. For this purpose one employs e.m. gauge invariance to express the "bad" electromagnetic current component (containing instantaneous terms) through the "good" component $J^A_+ = -q_+/q_- J^A_-$ [8]. In the approximation when non-nucleonic degrees of freedom in the deuteron wave function can be neglected, one can unambiguously relate the light-cone wave functions to those calculated in the lab. frame by introducing the LC pn relative three momentum $k = \sqrt{\frac{m^2+p_t^2}{\alpha(2-\alpha)} - m^2}$.

Turning to numerical estimates, it is worth noting that it is well established that, by using a polarized deuteron target in $(e,e'p)$ reactions, one can decisively disentangle the VN and LC prescriptions (see e.g. [8]). Now using the recent advances in the FSI calculation, one can repeat a similar comparison for the tensor asymmetry, $T^{20} = \frac{1}{3}(\sigma^{1,1}+\sigma^{1,-1}-2\sigma^{1,0})$, accounting also for the FSI diagrams. The result of such a comparison is presented in Fig.3 for backward kinematics ($\theta_s = 180^o$). One can see that account of the FSI further increases the difference between the predictions of the VN and LC approaches, thus making their experimental investigation more feasible.

The advantage of using a $\vec{d}$ target to enhance the contribution of small internucleon distances

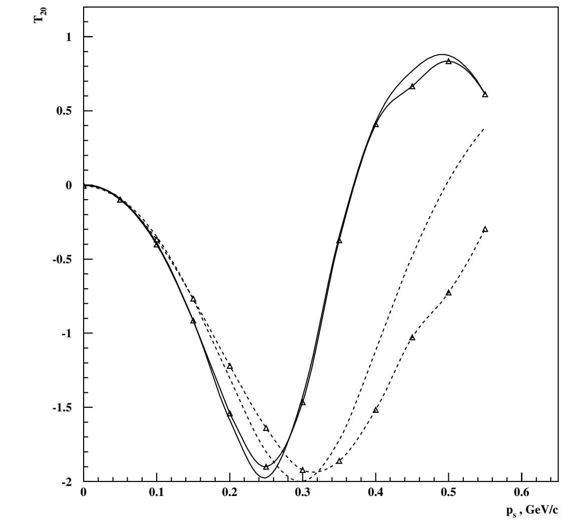

Figure 3: *p_s dependence of the $(e,e'p)$ tensor polarization at $\theta_s = 180^0$. Solid and dashed lines are PWIA predictions of the LC and VN methods, respective marked curves include FSI.*

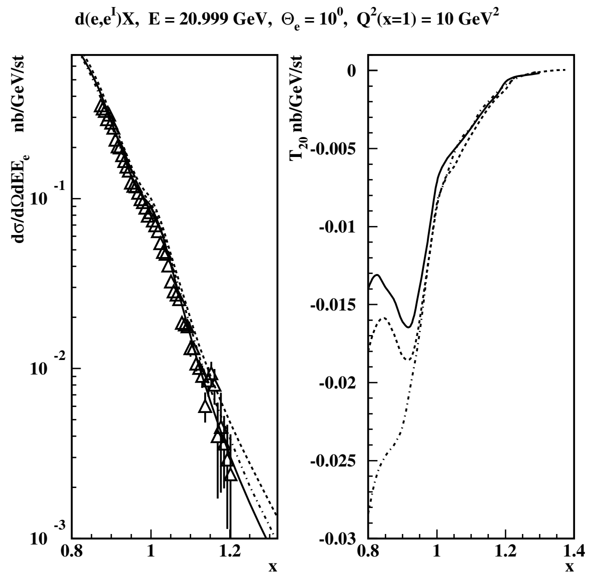

Figure 4: *Q^2 dependence of the unpolarized and tensor polarized cross sections. Solid line - LC approach with PLC suppression, dashed - LC, and dashed-dotted - VN. Experimental data from Ref.[9].*

holds even for inclusive $\vec{d}(e,e')$ scattering. In Fig.4, we compare the predictions of the VN and CT approaches for $d(e,e')$ reactions with unpolarized and polarized deuteron targets. Yielding practically the same predictions for a unpolarized target at $x < 1$, the two approaches differ by as much as a factor of two in the tensor polarization cross section.

3 Conclusions

We demonstrated that the use of a polarized deuteron target allows to probe effectively smaller internucleon distances in the deuteron ground state wave function for semiexclusive $(e,e'N)$ and inclusive (e,e') reactions. This opportunity can be successfully used to gain a better understanding of the structure of (moderate) high energy, large Q^2 eA interactions. In particular, we demonstrated that the use of a $\vec{d}$ target would allow to observe the onset of Color Transparency at intermediate energies as well as to confront different descriptions of relativistic effects in the deuteron and electromagnetic interactions with deeply bound nucleons.

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