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Model independent method for determination of the DIS structure of free neutron

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Abstract

We present a model independent procedure for extracting deep-inelastic structure function of "free" neutron from the electron–deuteron scattering with protons produced in the target fragmentation region of the reaction. This procedure is based on the extrapolation of t, which describes the invariant momentum transfered to the proton, to the unphysical region corresponding to the mass of the struck neutron. We demonstrate that the impulse approximation diagram of the reaction has a pole at this limit with a residue being proportional to the "free" neutron structure function. The method is analogous to that of Chew and Low for extraction of the "free" pion–pion and neutron–neutron cross sections from $p(\pi, p)X$ and $d(n,n)pn$ reactions, respectively. We demonstrate that in the extrapolation the final state interaction amplitudes are smooth functions of t and have negligible contribution in the extracted "free" nucleon structure function. We also estimate the range of the recoil nucleon momenta which could be used for successful extrapolation procedure.

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1. Introduction

In spite of three decades of studies of the partonic structure of nucleons one still lacks a satisfactory knowledge of the relative d and u quark densities at large Bjorken x region. To extract these quantities two major approaches have been considered to date: one is the neutrino scattering off the proton at large x which allows one to probe separately the u and d distributions. The second is the extraction of parton distributions from both protons and neutrons using inclusive scattering from the hydrogen and deuteron targets. (In the future it would be possible also to use $W^{\pm}$ production at LHC [1].)

While deep inelastic neutrino–proton scatterings lack adequate statistics, the inclusive electron–deuteron measurements suffer from significant nuclear effects an estimation of which involves the consideration of specific models for the Fermi motion and the EMC effect [2–5].

In our previous works [6–8] we outlined an alternative, model independent approach for extraction of "free" neutron deep inelastic structure function using semi-inclusive tagged neutron reactions, $d(e,e',p)X$, in which slow protons are detected in the target fragmentation region of the reaction. These considerations were incorporated in the experimental proposal which was approved and the measurements are currently under way at Jefferson Lab [9].[1] In this work we elaborate our approach quantitatively.

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[1] It is certainly of interest to study the reaction with tagged proton as well which would allow a direct comparison of the scattering off a free and bound proton and hence identify the processes beyond the impulse approximation.

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The extraction procedure is based on the observation that due to a weak binding in the deuteron the singularity of the amplitude in the $t = (p_d - p_p)^2$-channel is much closer to the physical region of on-shell neutron than to all other singularities. Hence one can in principle to continue analytically the scattering amplitude in t and find the residue at the pole of the struck neutron propagator at $t = m_n^2$. This is analogous to the Chew–Low procedure [10] for the extraction of $\pi\pi$ and nn cross sections from $p(\pi, p)X$ and $d(n, n)pn$ reactions, respectively. In their analysis they observed that the analytical structure of the impulse approximation amplitude (as in Eq. (4)) is such that it has a pole in nonphysical region of t corresponding to the one-mass-shell kinematics of the bound particles involved in the interaction. It is worth emphasizing that in our case the analytic continuation is simpler since the elementary amplitude does not contain factors which go through zero at t close to the pole of the amplitude ($t = 0$ as compared to $t = m_\pi^2$). Since procedures of extrapolation work well for the pion case, we expect them to be even more effective for the case of the tagged nucleon processes.

The Letter is organized as follows: in Section 2 we outline the general framework of semi-inclusive deep inelastic scattering off nuclear targets. In Section 3 we study the analytic properties of the impulse approximation and the final state interaction amplitudes at kinematics of recoil proton extrapolated to the pole values of the struck neutron propagator. In Section 4 we use a specific model to calculate the corrections to the impulse approximation due to the final state interactions. Based on this model we elaborate the extrapolation as well as free neutron structure function extraction procedures.

2. General framework

We consider semiinclusive deep inelastic scattering (DIS) off the deuteron:

$$e + d \to e' + N + X \tag{1}$$

in which nucleon N is detected in the target fragmentation region. We focus in the region of relatively large $x \geqslant 0.3$ were coherence length is small and hence nuclear shadowing effects [11] are negligible.

The processes of Eq. (1) with recoil proton can be used to extract the DIS structure function of the neutron. Since in this case the neutron is bound, it requires a careful treatment of off-shell effects in maximally model independent way. For this we will analyze analytic properties of the scattering amplitude of the reaction (1) focusing on the issues related to the extraction of the on-shell DIS structure function of the neutron.

First we summarize the general formulae for the cross section of process (1):

$$\frac{d\sigma}{dx\, dQ^2\, d^3p_s/E_s} = \frac{4\pi\alpha_{\rm em}^2}{xQ^4}\left(1 - y - \frac{x^2y^2m_N^2}{Q^2}\right) \times \left[F_L^D + \left(\frac{Q^2}{2q^2} + \tan^2\left(\frac{\theta}{2}\right)\right)\frac{\nu}{m_N}F_T^D + \left(\frac{Q^2}{q^2} + \tan^2\left(\frac{\theta}{2}\right)\right)^{1/2}\cos(\phi)F_{TL}^D + \cos(2\phi)F_{TT}^D\right], \tag{2}$$

where E_e is the initial energy of the electron and E'_e, θ are the energy and scattered angle of the final electron. The four-momentum of the virtual photon is $q \equiv (\nu, \vec{q})$, with $\nu = E_e - E'_e$ and $Q^2 = -q^2$. The recoil nucleon is described by four-momentum $p_s \equiv (E_s, \mathbf{p}_s)$. The invariant momentum transferred to the recoil nucleon is $t = (p_d - p_s)^2$, where p_d is the four-momentum of the deuteron. Four independent nuclear structure functions, $F^D_{L,T,TL,TT}$ depend on Q^2, x, α_s, p_{st}, with $\alpha_s = 2\frac{E_s - p_s^z}{m_D}$ being light cone momentum fraction of the deuteron carried out by recoil nucleon. The latter is normalized in such way that $\alpha_s + \alpha = 2$, where α is the similar quantity for the interacting nucleon. The Bjorken $x = \frac{Q^2}{2m_N\nu}$ and $y = \frac{\nu}{E_e}$. The z axis aligned in the direction of $\vec{q}$. In many practical considerations one integrates over the azimuthal angles ϕ of the recoil nucleon, which yields

$$\frac{d\sigma}{dx\, dQ^2\, d^3p_s/E_s} = \frac{4\pi\alpha_{\rm em}^2}{xQ^4}\left(1 - y - \frac{x^2y^2m_n^2}{Q^2}\right)\left[F_{\rm 2D}^{\rm SI} + 2\tan^2\left(\frac{\theta}{2}\right)\frac{\nu}{m_N}F_{\rm 1D}^{\rm SI}\right], \tag{3}$$

where: $F_{\rm 2D}^{\rm SI}(x, Q^2, \alpha_s, p_t) = F_L^D + \frac{Q^2}{2q^2}\frac{\nu}{m_N}F_T^D$ and $F_{\rm 1D}^{\rm SI}(x, Q^2, \alpha_s, p_t) = \frac{F_T^D}{2}$. The theoretical description of the reaction (1) at $p_s < 700\ {\rm MeV}/c$ is based on the assumption that it proceeds through the interaction of virtual photon off one of the bound nucleons in the deuteron, while produced particles can interact in the final state with the other (spectator) nucleon. Since $x \geqslant 0.3$, it is legitimate to neglect simultaneous interaction of γ^* with two nucleons. Two main diagrams will contribute to the cross section of reaction (1): impulse approximation (IA) (Fig. 1(a)) and diagram representing a rescattering of the recoil nucleon off the products of DIS scattering (Fig. 1(b)), which we will refer as final state interaction (FSI) diagram.