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SHADOWING IN INELASTIC LEPTON-DEUTERON SCATTERING

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Shadowing in inelastic lepton-deuteron scattering is analysed using the double interaction formalism where we relate shadowing to inclusive diffractive processes. Both the vector meson and parton contributions are considered for low and high Q^2 values including QCD corrections with parton recombination for high Q^2. These Q^2 values were chosen to correspond to existing experimental data and to the possible HERA measurements. Detailed discussion of various shadowing mechanisms is given. As expected the shadowing effects are found to be very small, less then 2% or so, in agreement with the recent precise measurements performed by the New Muon Collaboration. The contribution of shadowing term to the Gottfried sum from the region $x > 0.004$ and for $Q^2 = 4GeV^2$ is estimated to be equal to 0.025.

The term shadowing in inelastic lepton - nucleus scattering describes a phenomenon in which the nuclear structure function is less than A times the nucleon structure function where A is the mass number of a nucleus [1]. It is an established experimental fact [2] both for light and for heavy nuclei.

The purpose of this talk is to present the results of the theoretical analysis of shadowing in inelastic lepton-deuteron scattering. This presentation is based on the results obtained in ref. [3] where all the details can be found.

The deuteron structure function $F_{2D}(x,Q^2)$ is related in the following way to the proton and neutron structure functions $F_{2p}(x,Q^2)$ and $F_{2n}(x,Q^2)$ and to the shadowing term $\delta F_2(x,Q^2)$:

$$F_{2D}(x,Q^2) = F_{2p}(x,Q^2) + F_{2n}(x,Q^2) - 2\delta F_{2D}(x,Q^2) \quad (1)$$

where the relevant variables are

$$Q^2 = -q^2, \quad x = Q^2/p_D q \quad (2)$$

with the four momenta q and p_D corresponding to the virtual photon and to the deuteron respectively. The shadowing term $\delta F_{2D}(x,Q^2)$ is expected to be non-negligible in the region of small $x < 0.1$ or so.

It has traditionally been assumed that the shadowing term $\delta F_{2D}(x,Q^2)$ is very small since the deuteron is the loosely bound system. There are at least two reasons for revising the question to which extent the deuteron can be treated as a set of two free nucleons.

(1) The inelastic lepton deuteron scattering *serves* as the unique tool for determining the neutron structure function F_n. The recent measure-

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ments of the structure function ratio F_{2D}/F_{2p} performed by the New Muon Collaboration [4] are very precise and so even the relatively small shadowing term can in principle affect the extraction of the *neutron structure function* out of experimental data. It can in turn affect determination of other quantities, like for instance the Gottfried sum I_G [5]:

$$I_G(Q^2) = \int_0^1 \frac{dx}{x}[F_{2p}(x,Q^2) - F_{2n}(x,Q^2)] \quad (3)$$

(2) In the region of very small values of $x \ll 10^{-2}$ or so and for large Q^2 which may become accessible in the possible HERA measurements the shadowing should reveal various QCD effects including in particular the gluon recombination from two different nucleons in the deuteron [3,6].

Our aim will be to quantitatively estimate the nuclear shadowing in the deuteron in the kinematical region covered by the recent NMC data as well as in the region typical for the possible HERA measurements.

In the region of large Q^2 we expect that the interaction of the virtual photon with the deuteron is described by the "hand-bag" diagram of fig.1. In this region the parton model is applicable which leads to Bjorken scaling mildly violated by the perturbative QCD corrections. The parton model is described by the "hand-bag" diagram for the virtual Compton amplitude (fig.1). It is this hand-bag structure of the diagram which guarantees Bjorken scaling [7] (modulo perturbative QCD corrections) independently of the structure of the lower part of this diagram.

One can represent this diagram as the sum of two terms (a) and (b) which correspond to different number of nucleons participating in the interaction with the virtual photon. The structure function corresponding to the diagram (a)

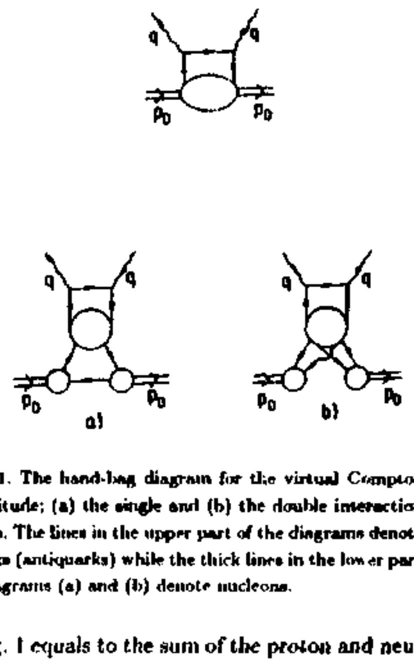

Fig. 1. The hand-bag diagram for the virtual Compton amplitude; (a) the single and (b) the double interaction terms. The lines in the upper part of the diagrams denote quarks (antiquarks) while the thick lines in the lower part of diagrams (a) and (b) denote nucleons.

of fig. 1 equals to the sum of the proton and neutron structure functions while the shadowing is given by the diagram (b) of fig.1 in which both nucleons participate in the interaction. The different models of shadowing correspond to different structure details of this diagram.

In the small x region one expects that the double interaction term is dominated by the double pomeron exchange that relates the shadowing to the diffractive production induced by virtual photons i.e.:

$$\delta F(x,Q^2) = \int d^2\mathbf{k}_\perp \int_{\xi_0}^1 d\xi S(\mathbf{k}^2)\frac{\partial^2 F_2^{diff}}{\partial\xi\partial t} \quad (4)$$

In this formula $S(\mathbf{k}^2)$ is the deuteron form-factor and $\frac{\partial^2 F_2^{diff}}{\partial\xi\partial t}$ is the *diffractive structure function* [8]. We define $\xi = 2kq/p_Dq$ where $\mathbf{k}$ is the four momentum corresponding to pomeron, $\xi_0 = x(1 + M_{x0}^2/Q^2)$ where M_{x0}^2 is the lowest mass squared of the diffractively produced hadronic system. We also have $t \cong -\mathbf{k}_\perp^2 - k_\parallel^2$ where $k_\parallel^2 = m^2\xi^2$ with m being equal to nucleon mass.

The diffractive structure function $\frac{\partial^2 F_2^{diff}}{\partial\xi\partial t}$ is related to the pomeron structure function $F_2^{(P)}(x/\xi, Q^2, t)$ [8]:

$$\frac{\partial^2 F_2^{diff}}{\partial\xi\partial t} = \frac{\beta^2(t)}{16\pi\xi} F_2^{(P)}(x/\xi, Q^2, t) \tag{5}$$

where $\beta(t)$ denotes the pomeron coupling to the nucleon. The pomeron structure function $F_2^{(P)}(x', Q^2, t)$ is parameterized as below:

$$F_2^{(P)}(x', Q^2, t) \cong F_2^{(P)}(x', Q^2, t=0)$$
$$= \frac{aQ^2}{(Q^2 + Q_0^2)} + bx'(1-x') \tag{6}$$

with the first and the second term corresponding to the triple pomeron and the quark box diagram contributions respectively. It should be noticed that *the x' scaling of the pomeron structure function* implies the Bjorken scaling of the shadowing term $\delta F_2(x, Q^2)$ for large Q^2. The formulas (4) to (6) define the partonic mechanism of shadowing suitably extended to the region of low Q^2.

The region of low M_x^2 where M_x is the mass of the diffractively produced system is dominated by the *diffractive production of low-mass* vector mesons. It is assumed to be described by the vector meson dominance model. In this model the contribution of low mass vector mesons to nuclear shadowing corresponds to double scattering of vector mesons which are coupled to virtual photons (fig.2). One gets then:

$$\delta F_{2D}^{(v)} = \frac{Q^2}{4\pi} \sum_v \frac{M_v^4 \delta\sigma_{vD}}{\gamma_v^2 (Q^2 + M_v^2)^2} \tag{7}$$

where M_v is the mass of the vector meson v and the constants γ_v^2 can be calculated from the leptonic widths of the vector meson v. The cross-section $\delta\sigma_{vD}$ is given by:

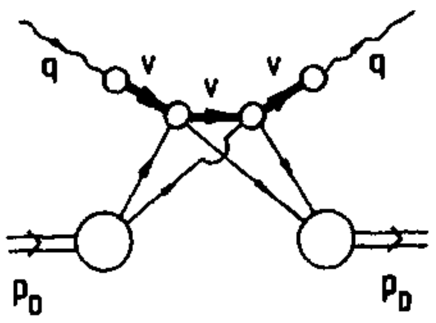

Fig. 2. Double scattering of vector mesons.

$$\delta\sigma_{vD} = \frac{1}{16\pi^2}\sigma_{vN}^2 \int d^2\mathbf{k}_\perp S(\mathbf{k}^2) \tag{8}$$

where now $k_\parallel^2 = m^2x^2(M_v^2/Q^2 + 1)^2$ and σ_{vN} is the total vector meson-nucleon cross section. In our calculations we shall include the contribution of ρ, ω and ϕ mesons. As can be seen from eq. (7) the double scattering of vector mesons gives vanishing contribution to shadowing in the large Q^2 limit.

Contribution from masses higher than M_ϕ will be related to the partonic mechanism of shadowing as decribed above. In our estimate of shadowing coming from the partonic mechanism we do therefore set the parameter $M_{x0}^2 > M_\phi^2$ (the magnitude of M_{x0}^2 is of course irrelevant in the large Q^2 limit). This choice of M_{x0}^2 guarantees avoiding of double counting in δF_{2D} when summing the partonic mechanism and the rescattering of vector meson parts of shadowing. These two parts just refer to two separate regions of M_x^2.

In fig.3 we plot our results for δF_{2D} as functions of x for fixed values of Q^2. We also plot the vector meson $\delta F_{2D}^{(v)}$ and parton mechanism contributions $\delta F_{2D}^{(p)}$ to shadowing. The pattern of x-dependence changes weakly with Q^2. The x-dependence is determined by the "$1/\xi$" diffractive spectrum (eqs. (5) and (6)) for small values of x and by the deuteron form-factor for higher values of x. The latter stems from the fact that the form factor argument, $\mathbf{k}^2$, depends upon ξ. The x dependence of $\delta F_{2D}^{(v)}$ is driven entirely by the form factor since we used the energy independent total cross-sections σ_{vN}. The deuteron structure function (normalized per nucleon) is equal to about 0.25 at $Q^2 = 1GeV^2$, almost independently of x, for $x < 0.1$ [2a]. Shadowing of high energy virtual photons in deuteron is then at most a 2-3 % effect. Using the results presented in fig. 3 we may estimate the contribution of shadowing to the Gottfried sum $\Delta I_G(x > x_{min}, Q^2)$ defined as:

$$\Delta I_G(x > x_{min}, Q^2) = -2\int_{x_{min}}^{0.1} \frac{dx}{x} \delta F_{2D}(x, Q^2) \tag{9}$$

For $Q^2 = 4GeV^2$ and for $x_{min} = 0.004$ (i.e for the values corresponding to the experimental measurements [4]) we find:

$$\Delta I_G(x > x_{min}, Q^2 = 4GeV^2) = -0.025 \tag{10}$$

The independent estimate of ΔI_G from the region $x > 0.004$ presented in ref. [5] which is based on different model of diffractive production gives: $\Delta I_G = -0.043$.

It should be noticed that the relation between the Gottfried sum and the measured structure functions F_{2D} and F_{2p} in the presence of shadowing is as below:

$$I_G(x_{min}, x_{max}, Q^2) \equiv \int_{x_{min}}^{x_{max}} \frac{dx}{x}[F_{2p}(x, Q^2) - F_{2n}(x, Q^2)]$$
$$= \int_{x_{min}}^{x_{max}} \frac{dx}{x}[2F_{2p}(x, Q^2) - F_{2D}(x, Q^2)] + \Delta I_G(x > x_{min}, Q^2) \tag{11}$$

The shadowing leads to negative sign of ΔI_G i.e. to smaller I_G than that determined experimentally assuming no shadowing. The experimental measurements give for the first integral in the right hand side of the equation (11) the value $I_G^{exp} = 0.227 \pm 0.007(stat.) \pm 0.014(\text{syst.})$ for $x_{min} = 0.004$, $x_{max} = 0.8$ and $Q^2 = 4GeV^2$ [4b].

We shall now discuss possible QCD effects on shadowing.

In the large Q^2 region δF_{2D} is related to the shadowing terms in the quark (δq) and antiquark ($\delta \bar{q}$) distributions in the deuteron:

$$\delta F_{2D} = x \sum_{flavours} e_i^2(\delta q_i + \delta \bar{q}_i) \tag{12}$$

The shadowing terms δg are also present in the gluon distributions in the deuteron. They can be related to the gluon distributions in a pomeron [3,9].

There are two possible QCD effects which can modify shadowing contribution to parton distributions:

(1) mild scaling violations induced by the QCD evolution,

(2)possible recombination of partons from different nucleons which gives additional terms in the evolution equations [3,6]. Those terms are sensitive upon the small x behaviour of gluon distributions in the nucleon.

The QCD corrections to shadowing become important in the region of very small values of x and for moderately large values of Q^2, that is in the kinematical range of the possible HERA measurements. They are displayed in fig. 4 and compared with the prediction of the partonic mechanism without QCD evolution which is represented by the dashed line in fig. 4. The QCD

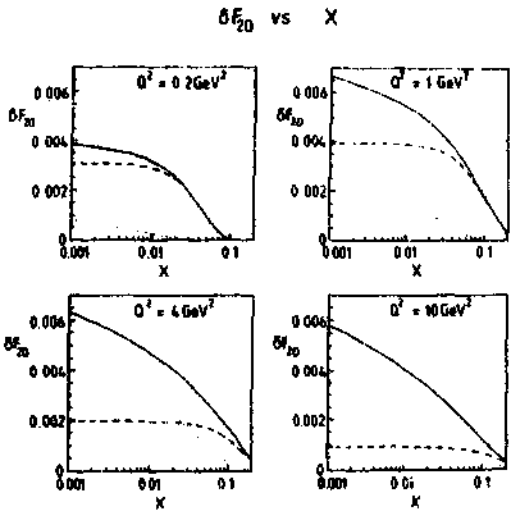

Fig. 3. Results for δF_{2D} as functions of x for fixed values of Q^2 (continuous lines). The dotted curves mark the $\delta F_{2D}^{(p)}$ and the dashed lines the $\delta F_{2D}^{(v)}$ contributions.

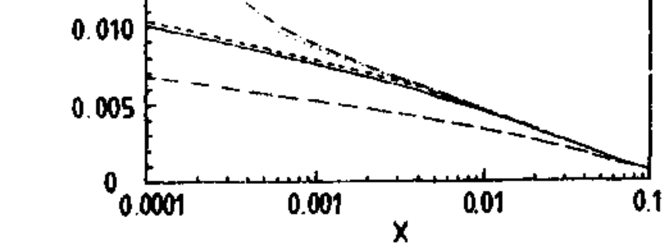

Fig. 4. Effects of QCD evolution on δF_{2D} for $Q^2 = 10\mathrm{GeV}^2$(no vector meson contribution). Long dashed curves shows unevolved δF_{2D} while the remaining four lines show the effects of the QCD evolution as described in the text.

evolution changes substantially the results at low x values. The evolution which neglects the parton recombination terms which is represented by the continuous line in fig.4 leads to an increase of δF_{2D} from 0.007 to 0.01 at $x = 10^{-4}$ and $Q^2 = 10 GeV^2$. This is a consequence of large amount of gluons in the pomeron enhancing the amount of quarks and antiquarks through the QCD evolution. The parton recombination mechanisms are very sensitive to the gluon distributions $xg(x, Q^2)$ in the nucleon at low x. In fig.4 we show the differences between results on δF_{2D} for three possible gluon parameterizations in the nucleon which differ by their behaviour at the x = 0 limit [10]. Thus the short dashed line corresponds to $xg(x,Q^2) \rightarrow$ const for $x \rightarrow 0$, the dotted curve corresponds to the gluon distribution containing both the singular $x^{-1/2}$ behaviour and shadowing effects and the dashed-dotted line shows results for $xg(x,Q^2) \rightarrow x^{-1/2}$. The structure function F_{2D} is also very sensitive to the gluon distributions in that region and therefore the shadowing is again only a 2% effect.

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