Nuclear phenomena at HERA energies

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Abstract

We argue that current data on nuclear shadowing confirm expectations of the color singlet models of nuclear shadowing. We demonstrate that unitarity constrains require nuclear shadowing for gluons to be very significant already for $x \lesssim 10^{-3}$. Physics of coherent diffraction production of vector mesons off light nuclei is also discussed.

1. Nuclear shadowing for parton distributions for $x \sim 10^{-2}$

Use of nuclear targets in DIS provides sensitive tests of interplay of perturbative and nonperturbative dynamics in small $x$ QCD. Currently the most revealing example is the nuclear shadowing phenomenon. Historically two qualitatively different QCD hypotheses were made about the dominant source of nuclear shadowing at small $x$. One was fusion of combining partons from different nucleons [1, 2, 3] another was color screening mechanism [4, 5, 6, 7] in which dominant mechanism of shadowing is soft color singlet interaction of $q\bar{q}$ pairs of transverse close to the hadron size with nucleons of the target. The second mechanism is a QCD extension of the parton model observation of Bjorken that $q\bar{q}$ hadron-like configurations in the virtual photon give a leading twist, scaling contribution to the deep inelastic cross section - the so called aligned jet model [8].

Two key predictions of the color singlet mechanism are now confirmed experimentally - NMC has finally observed [9] the pattern of scaling violation predicted in [3], diffraction in DIS expected in the color screening mechanism [3, 4] to be the leading twist effect was observed in DIS off nuclei [10] and at HERA. It is worth emphasizing that in the fusion mechanism no leading twist diffraction is expected since no color singlet is exchanged in $t$- channel.

The QCD analysis [3] indicates that at intermediate $Q^2$ shadowing is present in all channels - gluons, sea and valence quarks while the enhancement at larger $x \sim 0.1$ is present for valence quarks and gluons only. Further experimental studies are necessary to check these predictions.

Current versions of the color screening models usually assume that the eikonal type interactions with color singlet $q\bar{q}$ pair dominate. The average cross section for this interaction is about 15-18 mb for $\nu \sim 200$ GeV

* Talk given in the nuclear session at the Workshop on Deep Inelastic scattering and QCD, Paris, April 1995

Résumé

Nous montrons que les données actuelles concernant l’effet d’écrantage nucléaire confirment les prévisions des modèles de “couleur singlet” d’écrantage nucléaire. Nous demontrons que les contraintes d’unitarité exigent que l’effet d’écrantage nucléaire pour les gluons doit être déjà très significatif pour les $x \lesssim 10^{-3}$. Nous discuterons aussi de la physique de la production diffractive cohérente des mesons vecteurs sur un noyau léger.

1. Écra ntement pour les distributions des partie ns pour $x \sim 10^{-2}$

L’utilisation de cibles nucléaires dans la DIS fournit des tests sensibles de l’interplay de dynamique perturbation et nonperturbation dans les valeurs petites $x$ QCD. Actuellement l’exemple le plus révélateur est l’effet d’écrantage nucléaire. Historiquement deux hypothèses qualitativement différentes de QCD ont été faites au sujet de la source dominante de l’écrantage nucléaire à petite $x$. Une était la fusion de combinaison de partons provenant de différents noyaux [1, 2, 3] et une autre était le mécanisme d’écrantage à couleur singlet [4, 5, 6, 7] dans lequel le mécanisme dominant de l’écrantage est l’interaction color singlet de $q\bar{q}$ à distance transverse proche de la taille du hadron avec les noyaux de la cible. Le second mécanisme est une extension QCD de l’observation du parton modèle de Bjorken que $q\bar{q}$ configurations de hadrons dans le photon virtuel donnent une contribution de twist dominant, scaling contribution à la section profonde inélastique - le modèle alig ne jet [8].

Deux prédictions clés du mécanisme à couleur singlet sont maintenant confirmées expérimentalement - NMC a finalement observé [9] le motif de violation de scaling prédit dans [3], la diffraction en DIS attendue dans le mécanisme d’écrantage à couleur singlet [3, 4] a été observée en DIS sur des noyaux [10] et à HERA. Il est worth emphasizing que dans le mécanisme de fusion, aucune diffraction de twist dominante n’est attendue car aucune couleur singlet n’est échangée dans $t$- canal.

L’analyse QCD [3] indique que dans les valeurs moyennes $Q^2$ l’écrantage est présent dans tous les canaux - gluons, mer et quarks valence alors que l’augmentation à des valeurs plus grandes $x \sim 0.1$ est présente pour les quarks valence et gluons seulement. Les études expérimentales sont nécessaires pour vérifier ces prédic tions.

Les versions actuelles des modèles d’écrantage à couleur screening généralement supposent que les interactions eikonal type avec la couleur singlet $q\bar{q}$ pair dominent. La section moyenne de cette interaction est d’environ 15-18 mb pour $\nu \sim 200$ GeV.
Fluctuations in the interaction cross section lead to a small correction only. However in QCD mechanism of shadowing is more complicated since the interaction of small transverse size $q\bar{q}$ configurations (which are not screened in the eikonal approximation) is given by (11).

$$\sigma(b^2) = \frac{\pi^2}{3} \left[ b^2 \alpha_s(Q^2) xG_T(x, Q^2) \right]_{x=Q^2/s, Q^2 \approx 15/b^2} \ , \ (1)$$

One can see from this equation that as soon as gluon shadowing is present interaction of small size $q\bar{q}$ configurations is screened as well in the leading twist. To study interplay of the contribution of small and large size configurations it is necessary to study in greater detail diffractive processes. We find that total cross section of any deep inelastic hard process at small $x$ and fixed $Q^2$ is expected to fulfill the following relation: (4)

$$\frac{\sigma_{coh, diffr.}}{\sigma_{tot}} \approx 0.1 \left( \frac{A}{10} \right)^{0.25} \ (2)$$

This value is consistent with the observations of E-665 (10). Clearly to get a deeper insight into dynamics of shadowing one has to study the final states in a more exclusive way.

2. Physics issues for Nuclear beams at HERA

Currently there is discussion of studies of DIS scattering off nuclei at HERA. This could open qualitatively new opportunities for understanding of the small $x$ dynamics and would have serious impact for the studies of $AA$ collisions at LHC.

2.1. Shadowing of hard processes at very small $x$

Cross section of any deep inelastic hard process at small $x$ can be expressed in the leading twist through the cross section of interaction of $q\bar{q}$ pairs of different transverse size, $b$ with the target. However analysis of eq. (1) indicates that at very small $x$ this equation should break down since it violates the unitarity limit which requires that inelastic cross section for the hard interaction of a system of transverse area $S$ cannot exceed $\sigma_{inel} \leq S$. This condition has earliest practical implications in the case of heavy nuclei where it corresponds to (12, 13)

$$\alpha_s(Q^2) xG_A(x, Q^2) \leq \frac{1.9 Q^2}{A^{1/3}} \ (3)$$

Equation (3) indicates that hard processes sensitive to gluon densities in nuclei at small $x$ and moderate $Q^2 \leq 10 GeV^2$ should be strongly shadowed. For example, in the case of $\sigma_T(A)$ we find that for $Q^2 = 10 GeV^2$ it cannot exceed the value corresponding to $xG_T^{1/f}(x, Q^2) \leq \frac{30}{A^{1/3}}$. Soft gluons are expected to be shadowed strongly as well (stronger than soft quarks) (4). Therefore very significant shadowing is expected for $\sigma_L(A)$ for large $A$ at $x \leq 10^{-2}$.

An increase of shadowing for $\sigma_T(A, x, Q^2)$ in the limit of small $x$ and fixed $Q^2$ is also expected due to several effects: a) increase of the soft cross section with $s$ (as $s^n$ with $n \geq 0.08$, b) contribution of the triple Pomeron term, c) larger shadowing of the small size configurations due to larger gluon shadowing.

2.2. Nuclear effects in the diffraction production of vector mesons

2.2.1. Coherent production of vector mesons off nuclei at small $t$ The QCD analysis (13) confirms the conjecture of refs. (1, 14, 15) that at large $Q^2$ vector mesons are produced in small transverse size configurations (at least for the longitudinally polarized photons) and hence the color transparency phenomenon (CT) is expected. In the case of coherent vector meson production off nuclear targets QCD prediction, in the form of equation (4), with factor $A^2$ substituted by $(G_A(x, Q^2)/G_N(x, Q^2))^2$, absorbs all the dependence on the atomic number in the gluon and sea quark distributions of the target. But it is well known that the evolution of parton distributions with $Q^2$ moves the effect of nuclear shadowing to smaller $x$. Thus at small but fixed $x$ and sufficiently large $Q^2$ the cross section for hard diffractive processes is expected to fulfill the following relation:

$$\frac{d \sigma_{\gamma^*+A \rightarrow X+A \rightarrow X+A}}{dt}_{t=0} = A^2 \frac{d \sigma_{\gamma^*+N \rightarrow X+N}}{dt}_{t=0} \ (4)$$

This is the so called color transparency phenomenon which leads to the validity of the impulse approximation – the nucleus is transparent for the projectile and there is no final state interactions. The onset of CT should occur at moderate $Q^2$ since gluon shadowing disappears fast with increasing $Q^2$ at fixed $x$ (9). If the size of the configuration is fixed (at large but fixed $Q^2$) but the energy of the collision increases, shadowing effects should become more and more important since the gluon shadowing increases with decreasing $x$ (see figure 3). Moreover analysis of the unitarity constraints in Eq.(3) demonstrates that in the scattering off heavy nuclei screening effects should lead to very substantial suppression of coherent vector meson production cross section $\frac{d \sigma_{\gamma^*+A \rightarrow X+A \rightarrow X+A}}{dt}_{t=0}$ for $x \sim 10^{-4}, Q^2 \sim 10 GeV^2$.
as compared to the expectation of eq.\(6\). Thus the use of heavy nucleus beams would allow to observe nonlinear effects already in the HERA kinematics, while for the case of \(ep\) collisions similar effects are likely to be significant for \(x \lesssim 3 \cdot 10^{-5}\) only \(12\) which is beyond the HERA kinematics. Similar CT behavior is expected for the production of transversely polarized vector mesons but at significantly larger \(Q^2\) than for the longitudinally polarized vector mesons, real photons.

As explained above, the preliminary HERA data indicate that PQCD predictions contained in formula (1) are applicable already for \(Q^2 \sim 10\) GeV\(^2\). Obviously this is an implicit confirmation of the color transparency logic since it confirms both the presence of small transverse configurations in the \(\rho\) meson and the smallness of their interactions with hadrons. It would be important to investigate further these effects more directly at ultra high energies. To this end we consider briefly the scattering off the lightest nuclei \(13\). Note that there are discussions to accelerate deuterons at HERA and to polarize them in order to measure the parton distributions in the neutron.

2.2.2. Color transparency effects in \(\gamma L + D(A) \to V_L + D(A)\). The very existence of the color coherence effects leads to a rather nontrivial dependence of the cross sections of hard diffractive processes on \(x, Q^2\). To elucidate this point we consider in this section diffractive electroproduction of vector mesons off the deuteron.

First, let us consider the leading twist effect. It follows from eq.\(5\) that at \(t=0\) the amplitude of this process is proportional to the parton density in the deuteron. The nuclear effect in the leading twist depend on \(x, Q^2\) in a rather complicated way. At \(x \sim 0.1\) and \(Q^2 \sim few\ GeV^2\ - the kinematics of the HERMES facility the gluon density in nuclei is significantly enhanced: \(G_{A}(x, Q^2)/G_{N}(x, Q^2) > 1\). This effect follows from the need to reconcile the momentum and baryon sum rules with the \(F_2\) data \(15\). The dynamical mechanism relevant for the gluon enhancement is not understood so far.

Consequently QCD predicts an enhancement but not shadowing for the electroproduction of vector mesons at \(t = 0\) off the deuteron at \(x \sim 0.1\). This effect should die out rather rapidly with increase of \(Q^2\) due to the QCD evolution of parton distributions with \(Q^2\) (cf. Fig. for the \(Q^2\) dependence of parton distributions).

At sufficiently small \(x \leq 10^{-2}\) shadowing of gluon distribution dominates. We will restrict the discussion to the region of sufficiently large \(x \geq 10^{-4}\) where interaction of a small \(q\bar{q}\) state with a nucleon, \(\sigma_{q\bar{q}N}(b^2, x)\) which is given by eq.(1) is small as compared to the unitarity limit and therefore QCD evolution equations seem to be applicable. In this kinematics one expects a fast decrease of shadowing with increase of \(Q^2\).

Obviously, at \(t \approx t_{\text{min}}\) shadowing effects are small since inter-nucleon distance in the deuteron is comparatively large. To enhance these effects it would be advantageous to study experimentally the coherent electroproduction of vector mesons at \(|t| \geq 0.5 GeV^2\) where an interesting diffraction pattern with secondary maximum was observed long time ago for photoproduction of \(\rho\)-meson. This pattern at \(Q^2 = 0\) arises within the vector dominance model as a result of the vector meson rescatterings. At large \(Q^2\) QCD predicts more complicated behavior.

Let us consider firstly rescatterings of the produced \(q\bar{q}\) pair of small size \(b\). In this case the scattering amplitude is given by the sum of two terms, one given by the impulse approximation and the other due to double scattering:

\[
\frac{d\sigma_L(\gamma^* + D \to V + D)}{dt} = \frac{1}{16\pi} \int |2S_D(t)f_{\gamma^* N \to V N}(x, b^2, r_i) + \int d^2k_T[i\left(\frac{i}{8\pi}\right)f_{\gamma^* N \to V N}(x, b, Q^2, r_i/2 - k_i)\right] f_{q\bar{q}, N}(x, b, r_i/2 + k_i)S_D(4k_i^2)]\psi_{\gamma^*}(z, b, Q^2)\psi_V(z, b)dzd^2b| \sim 1,
\]

where \(t = -r_i^2\), \(S_D(t)\) is the deuteron form factor, and \(f_{q\bar{q}, N}(x, b, r_i/2 + k_i)\) is the amplitude for the elastic rescattering of the \(q\bar{q}\) pair. For simplicity we ignore here the spin indices. For the interaction of a small transverse size \(q\bar{q}\) configuration small impact parameters \(b\) dominate in equation\(16\). Hence the CT prediction of formula (4) is that at small but fixed \(x\) with increasing \(Q^2\) the relative contribution of the second term should be proportional to \(xG_N(x, Q^2)\). Since at \(-t \geq -t_0 \sim 0.5 GeV^2\) the elastic cross section is dominated by the square of the second term, this mechanism leads in this region to the cross section which is extremely sensitive to the CT effects. In particular, the ratio

\[
\left|\frac{d\sigma_L^* + D \to V + D}{dt}\right|_{-t \geq -t_0}/\left|\frac{d\sigma_L^* + D \to V + D}{dt}\right|_{-t = 0} = \left(\frac{1}{2}\right) \exp Bt \frac{x^2G_N(x, Q^2)}{4Q^4},
\]

where

\[
\langle\sigma_{q\bar{q}N}(b)\rangle = \int d^2b\psi_{\gamma^* N}(b)\psi_V(b)\sigma_{q\bar{q}N}(b) = \int d^2b\psi_{\gamma^* N}(b)\psi_V(b)\sigma_{q\bar{q}N}(b)\]

should strongly decrease with increasing \(Q^2\) and flatten for sufficiently large \(Q^2\) to a leading twist behavior due
to the space-time evolution of the $gq$ configurations. On the contrary at fixed $Q^2$ this ratio should increase with decreasing $x$. Here $B = B_{γN}/2$ with $B_{γN}$ denoting the slope of the differential cross section for the elementary $γ^* + N → V + N$ reaction and <(p) = ∫ d3r r−2|T(r)|2. The large $t$ ($−t ≥ 0.5 \text{ GeV}^2$) dependence of the cross section in equation 8, $|dt| ∝ \exp(B't)$ with $B' ≃ 2 \text{ GeV}^2$, is significantly weaker than in the Glauber model where $B'$ is expected to be

$$B' = \frac{B_{γN}B_{γN}}{B_{γN} + B_{γN}} ≃ 3 \text{ GeV}^2.$$ (10)

We neglected here the deuteron quadrupole form factor effects. They lead to a contribution to the cross section which does not interfere with the electric transition and for which Glauber effects are small. This contribution fills the minimum due to the interference of the impulse and double scattering terms 18. However this contribution to the cross section can be significantly suppressed by using a polarized deuteron target. Similar effects should be present for the scattering of heavier nuclei, like $3^4\text{He}$. The measurement of the depth of the Glauber minimum due to the interference of the amplitude given by the impulse approximation with rescattering amplitudes would allow to check another feature of expression (1), namely the large value of the real part of the production amplitude $Re f/Im f ∝ πn/2 ∼ 0.5$, where $n$ characterizes the rate of increase of the gluon density at small $x, xG_N(x, Q^2) ∝ x^{−n}$. In this discussion we neglected the leading twist mechanism of double rescattering related to the leading twist nuclear shadowing. It is likely to have similar $t$–dependence as the term we considered above. It may compete with the mechanism we discussed above in a certain $x, Q^2$ range. This question requires further studies. In any case it is clear that in a wide kinematic range the relative height of the secondary maximum would be strongly suppressed as compared to the case of the vector meson production by a real photon. At very small $x$ for $Q^2$ where $σ_{qN}$ is close to unitarity bound this suppression may disappear. This would establish the $x, Q^2$ range where color transparency should disappear.

Recent FNAL data on incoherent diffractive electroproduction of vector mesons off nuclear targets 20 did find an increase of nuclear transparency with increasing $Q^2$ as predicted in 4, 16, 17. However a significant effect is reported for a $Q^2$ and $x$ range where the average longitudinal distances are comparable with the nuclear radius $l_c = \frac{1}{2πnN} ∼ R_A$ and it is well known that at large $x$ shadowing disappears for hard processes. Thus it is necessary to investigate theoretically to what extent the observed increase of transparency is explained by the effects of finite longitudinal distances. The ideas discussed in this report do not apply directly to color transparency phenomena at moderate energies. For a recent review of this field we refer the interested reader to 21.

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