Color Transparency and Color Opacity in Coherent Production of Vector Mesons off Light Nuclei at small x

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Abstract: Coherent electroproduction of vector mesons off ^{2}H and ^{4}He is considered in the kinematics of deep inelastic scattering. Special emphasize is given to the $-t \sim 0.8 - 1GeV^2$ region where cross section is dominated by the interaction of $q\bar{q}$ configuration in γ^* with two nucleons. This kinematics provides unique possibilities to study quantitatively onset of Color Transparency in the vector meson production with increase of Q^2 as well as its graduate disappearance at very small x- perturbative Color Opacity.

1 Introduction

The recent theoretical analyses [1, 2, 3] have demonstrated that in the limit of large Q^2 exclusive production of vector mesons in the process $\gamma_L^* + p \to V + p$ is controlled by the calculable interplay of hard-perturbative QCD and nonperturbative QCD. Recent experimental data [4] seem to indicate that the hard mechanism starts to dominate already at $Q^2 \geq 5$ GeV^2.

In the small x region the vector meson production is essentially three stage process in the target rest frame. First, at the distance $l_c \sim \frac{1}{2m_N x}$ before the target γ_L^* transforms into a small transverse size $q\bar{q}$ pair: $b_{q\bar{q}} \equiv r_{qt} - r_{\bar{q}t} \approx 3/Q$ $b_{q\bar{q}}(Q^2 \sim 10GeV^2) \approx 0.4fm$; then the small $q\bar{q}$ pair interacts with the target with amplitude [5]:

$$A(q\bar{q}T)\mid_{t=0}= \frac{Q^2\pi^2}{3x}\left[b^2\alpha_s(Q^2)\cdot\left(i-\frac{\pi}{2}\frac{d}{lnx}\right)xG_T(x,Q^2)\right], \qquad (1)$$

where $G_T(x,Q^2)$ is the gluon density of the target. The third stage - transformation $q\bar{q} \to V$ occurs long after the target at distances $\sim 2q_0/m_V^2$. The use of the completeness over diffractively produced states allows to express the result in terms of bare parton distributions within a target and within the vector meson similar to the DIS processes[1] as: $A^{\gamma^*T\to VT} = \psi^{\gamma^*\to q\bar{q}} \otimes A(q\bar{q}T) \otimes \psi^{q\bar{q}\to V}$, where $\psi^{\gamma^*\to q\bar{q}}$ is the wave function of $\gamma^* \to q\bar{q}$ transition, $\psi^{q\bar{q}\to V}$ is the $q\bar{q}$ component of the V wave function. $A(q\bar{q}T)$ describes the $q\bar{q}$ scattering off target T with cross section given by eq.(1).

The use of the nuclei allows to check QCD prediction that cross section of interaction of small $q\bar{q}$ with a nucleon is indeed small - Color Transparency, and whether it can reach (due to increase of the gluon density at small x) values comparable to those for the interaction of light hadrons (pions) - perturbative Color Opacity. One possible strategy is to study coherent vector meson production of heavy enough nuclei at $t \sim 0$. Another possibility which we consider here is to use the process $\gamma^* + A \to V + A$ with the lightest nuclei (A=2,4), $V = \rho, \rho', \omega, \phi...$ at $x \leq 10^{-2}$ and focus on the region of comparatively large $|t|$ where **interaction with two nucleons dominate.** We restrict by the coherent channel because this case can be singled out experimentally in an unambiguous way. There is clear experimental evidence for the dominance of the rescattering diagrams in the coherent production off the deuteron at $|t| \geq 0.6 GeV^2$(see Ref.[6] and references therein). Due to the quadrupole contribution the diffractive minimum is filled up. This is the reason why our next choice is the ^4He target, which is a spherical nucleus without quadrupole form factors for which diffractive minimum occurs at $-t \sim 0.2 GeV^2$ and where, as a result, one is sensitive to rescatterings at considerably smaller $|t|$.

2 Cross Section

At small x, and large Q^2 where average $b_{q\bar{q}}$ is small, nuclear effects are generated through the double rescattering of the $q\bar{q}$ pair off the target nucleons. As a result of QCD evolution parton wave function of a compact configuration can evolve to normal hadron transverse size. Such a configuration will lead to shadowing effects in the leading power of Q^2. This effect is not too small at $t = 0$ at sufficiently small x [2].Thus in QCD there is no direct relation between smallness of cross section and smallness of secondary interactions. Strict QCD prediction is that double scattering effects should decrease with Q^2 increase more fastly than single scattering amplitudes [1] but actual calculation of double scattering term is model dependent at the moment. Hence we account for double scattering of q$\bar{q}$ pair which is numerically large and neglect leading twist effects due to QCD evolution of the q$\bar{q}$ pair to normal hadron size which decrease with t more rapidly. For the deuteron we obtain (suppressing spin indices):

$$\frac{d\sigma^{\gamma_L^* {}^2H \to V {}^2H}}{dt} = \frac{1}{16\pi}\left|2f^{(1)}(t)S_d(\frac{q}{2}) + \frac{i}{2}f^{(2)}\left(\frac{t}{2}\right)\int\frac{d^2k'_\perp}{(2\pi)^2}S_d(k'_\perp)e^{-Bq'^2}\right|^2 \tag{2}$$

where $t \approx -q_\perp^2$ and $S_d(k) = F_c(q) + \left(3\frac{(Jq)^2}{q^2} - 1\right)F_Q(q)/\sqrt{2}$ and F_C and F_Q represents the charge and quadrupole deuteron form factors. Similarly for the coherent scattering off ^4He we obtain:

$$\frac{d\sigma^{\gamma_L^* {}^4He \to V {}^4He}}{dt} = \frac{1}{16\pi}\left|4f^{(1)}(t)\Phi(t) + \frac{i3f^{(2)}(\frac{t}{2})}{4\pi(\alpha+B)}e^{\frac{\alpha}{8}t}\right|^2 \tag{3}$$

where $\Phi(t)$ is the charge form factor of ^4He ($\Phi(t) \approx \exp(3\alpha t/3)$ for small t). We restrict ourselves by the calculation of double scattering amplitudes since multiscattering amplitudes violate energy-momentum conservation in respect to production of multiparticle states. So their contribution should be 0 (S.Mandelstam cancelation) within the approximation when only a q$\bar{q}$ pair is considered. In Eqs.(2) and (3) the multiple scattering amplitudes are defined as:

$$f^{(n)} \sim \int d^2b\psi^L_{\gamma^*}(b)\psi_V(b)\sigma^n_{q\bar{q}N}(b)exp(Bt/n) \tag{4}$$

where $\sigma_{q\bar{q}}$ is given by eq.(1). Because of the small size of $q\bar{q}$ the slope of the elementary amplitude, $B \approx 2.5\ GeV^{-2}$[4] is mainly determined by the two-gluon nucleon form factor

3 Onset of Color Transparency (CT)

The onset of CT leads to a rather nontrivial dependence of the coherent production cross section on x, t and Q^2. To estimate the effects we analyze the ratio $R(t) = \frac{d\sigma^{\gamma_L^*}}{dt}(t)/\frac{d\sigma^{\gamma_L^*}}{dt}(t=0)$. It follows from eqs.(2-4) that at $-t \geq -t_0 \sim 0.5\ GeV^2$ (> 0.2GeV^2 for $A = 4$) when coherent cross sections are dominated by rescattering terms, the $R(|t| > |t_0|) \sim x^2G_N^2(x,Q^2)e^{Bt}/Q^4$. Therefore one should expect the strong decrease of R with increasing Q^2. At the same time for fixed Q^2 one expects a fast increase of the cross section with decrease of x. This increase

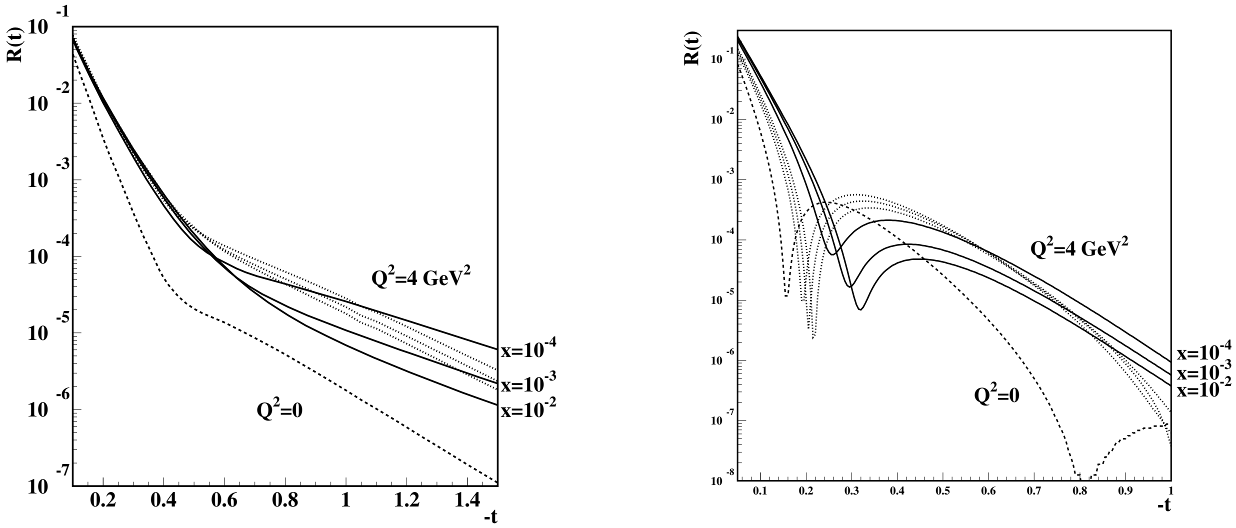

Figure 1: *The $R(t)$ as a function of t at different x. Solid curves - QCD calculation explained in text, dotted curves are VMD predictions, dased curve is for $Q^2 = 0$, which for ^4He include $n > 2$ rescattering term.*

is restricted by unitarity condition[3]. An observation of a slowing down of such an increase at small x would be a clear signature of the onset of color opacity. For $Q^2 \sim 5GeV^2$ such effect could occur already at HERA energies.

In Fig.1 we present $R(t)$ for fixed Q^2 and different x, calculated for coherent scattering off d and ^4He. We show also in this figure expectation of the Vector Dominance model (VMD) in which ρ-meson is produced in the first interaction and scatters off the nucleons with cross section similar to πN cross section. In the case of ^4He target one expects a clean minimum which is very sensitive to amount of rescattering terms in eq.(4). Investigation of the depth of diffraction minima would allow to check another prediction of QCD, namely the large value of the real part of the production amplitude $ReF/ImF \sim 0.3 - 0.4$.

3 Critical Assessments and Conclusions

In this discussion we assumed that the only mechanism that generates the nuclear effects are double rescatterings and neglected the leading twist mechanism of multiple scattering related to the leading twist nuclear shadowing. It may compete with the mechanism we discussed above in a certain x, Q^2 range. This question requires further studies and detailed experimental study of t, x Q^2 dependences at large kinematical range is necessary. However the important signature which will be held at the wide kinematical range is that relative contribution of the secondary rescatterings would be strongly suppressed as compared to the case of the real photon projectile. If such a suppression will disappear at very small x close to unitarity bound, this would establish the x, Q^2 range for onset of the Color Opacity phenomenon.

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