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 emphasis is given to the \( -t \sim 0.8 - 1 \) GeV\(^2 \) region where the cross section is dominated by the interaction of the \( q\bar{q} \) configuration in the \( \gamma^* \) with two nucleons. These kinematics provide the unique possibilities to study quantitatively in vector meson production the onset of Color Transparency with increasing \( Q^2 \) as well as its gradual disappearance at very small \( x \), i.e., perturbative Color Opacity.

1 Introduction

Recent theoretical analyses \cite{1,2,3} have demonstrated that, in the limit of large \( Q^2 \), exclusive production of vector mesons in the process \( \gamma_L^* + p \rightarrow V + p \) is controlled by the calculable interplay of hard perturbative QCD and soft nonperturbative physics. Recent experimental data \cite{4} seem to indicate that the hard mechanism starts to dominate already at \( Q^2 \geq 5 \) GeV\(^2 \).

In the small \( x \) region, vector meson production in the target rest frame is essentially a three stage process. First, at a distance \( \ell_c \sim \frac{1}{2m_Nx} \) before the target, the \( \gamma_L^* \) transforms into a small transverse size \( q\bar{q} \) pair where \( b_{q\bar{q}} \equiv r_{q\bar{q}} - r_q \approx 3/Q \), i.e., \( b_{q\bar{q}}(Q^2 \sim 10 \) GeV\(^2 \) \) \( \approx 0.4 \) fm. Then, the small \( q\bar{q} \) pair interacts with the target with an amplitude \cite{3}:

\[
A(q\bar{q}T) \big|_{t=0} = \frac{Q^2 \alpha_s^2}{3x} \left[ b^2 \alpha_s(Q^2) \cdot \left( i - \frac{\pi}{2 m_N x} \right) xG_T(x,Q^2) \right],
\]

where \( G_T(x,Q^2) \) is the target’s gluon density. The third stage, the transformation \( q\bar{q} \rightarrow V \) occurs long after the target at distances \( \sim 2q_0/m_V^2 \). The use of completeness over the diffractionally produced states allows to express the result in terms of bare parton distributions within the target and the vector meson similar to DIS processes \cite{1}: \( A^{\gamma^*T\rightarrow VT} = \psi^{\gamma^*\rightarrow q\bar{q}} \otimes A(q\bar{q}T) \otimes \psi^{q\bar{q}\rightarrow V} \), where \( \psi^{\gamma^*\rightarrow q\bar{q}} \) is the wave function of the \( \gamma^* \rightarrow q\bar{q} \) transition, \( \psi^{q\bar{q}\rightarrow V} \) is the \( q\bar{q} \) component of the \( V \)'s wave function. \( A(q\bar{q}T) \) describes the scattering of the \( q\bar{q} \) off the target \( T \) with a cross section given by Eq.(1).

The use of nuclei allows to check the QCD prediction that the interaction cross section of a small \( q\bar{q} \) with a nucleon is indeed small, i.e., Color Transparency, and whether it can reach (due to the increase of the gluon density at small \( x \)) values comparable to those for the interaction of light hadrons (pions), i.e., perturbative Color Opacity. One possible strategy is to study coherent vector meson production off heavy enough nuclei at \( t \sim 0 \). Another possibility, which we consider here, is to use the process \( \gamma^* + A \rightarrow V + A \) with the lightest nuclei (A=2,4) for \( V = \rho, \rho', \omega, \phi... \) at \( x \leq 10^{-2} \), and to focus on the region of comparatively large \( |t| \), where the interaction with two nucleons dominates. We restrict ourselves to 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.[3] and references therein). Due to the quadrupole contribution, the diffractive minimum is filled up. This is the reason why our next choice is a $^4$He target, which is spherical and without quadrupole form factors, and for which the diffractive minimum occurs at $-t \sim 0.2$ GeV$^2$. There, as a result, one is sensitive to the rescatterings at considerably smaller $|t|$.

2 Cross Section

At small $x$ and large $Q^2$, where the average $b_{q\overline{q}}$ is small, nuclear effects are generated through double rescattering of the $q\overline{q}$ pair off the target nucleons. As a result of QCD evolution, the parton wave function of a compact configuration can evolve to normal transverse hadronic size. Such configurations will lead to shadowing effects in the leading power of $Q^2$. This effect is not too small at $t = 0$ at sufficiently small $x$ [3]. Thus, in QCD, there is a direct relation between the smallness of the cross section and the smallness of secondary interactions. A strict QCD prediction is that double scattering effects should decrease with increasing $Q^2$ more fastly than the single scattering amplitudes [4]. But an actual calculation of the double scattering term is model dependent at the moment. Hence, we account for double scattering of the $q\overline{q}$ pair, which is numerically large, and neglect leading twist effects due to QCD evolution of the $q\overline{q}$ pair to normal hadronic size, which decrease with $t$ more rapidly. For the deuteron, we obtain (suppressing spin indices):

$$\frac{d\sigma^\gamma\gamma^{2H\to V^2H}}{dt} = \frac{1}{16\pi} \left| 2f^{(1)}(t) S_d(t) + \frac{i}{2} f^{(2)}(\frac{t}{2}) \int \frac{d^2k'}{(2\pi)^2} S_d(k') e^{-B_{q\overline{q}}^2} \right|^2$$

(2)

where $t \approx -q_1^2$ and $S_d(k) = F_c(q) + (3\sqrt{3}q^2 - 1) F_Q(q)/\sqrt{2}$. $F_c$ and $F_Q$ represent the deuteron’s charge and quadrupole form factors. Similarly, for coherent scattering off $^4$He, we obtain:

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

(3)

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

$$f^{(n)} \sim \int d^2b \psi_{\gamma^*}^L(b) \psi_V(b) \sigma_{q\overline{q}N}(b)e^{\exp(Bt/n)}$$

(4)

where $\sigma_{q\overline{q}}$ is given by Eq.(4). Because of the small size of $q\overline{q}$, the slope of the elementary amplitude, $B \approx 2.5$ GeV$^{-2}$ [4], is mainly determined by the nucleon’s two-gluon 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 those effects, we analyze the ratio $R(t) = \frac{d\sigma^\gamma\gamma^{2H}}{dt}(t)/\frac{d\sigma^\gamma\gamma^{2H}}{dt}(t = 0)$. It follows from Eqs.(2-3) that at $-t \geq -t_0 \sim 0.5$ GeV$^2$ ($> 0.2$ GeV$^2$ for $A = 4$), when the coherent cross sections are dominated by the rescattering terms, $R(|t| > |t_0|) \sim x^2G_k^2(x, Q^2)e^{Bt}/Q^4$. Therefore, one should expect a 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 decreasing $x$. This increase is restricted by a unitarity condition [3]. An observation of a slowing down of such an increase
Figure 1: \( R(t) \) as a function of \( t \) at different \( x \). Solid curves are QCD calculations as explained in text, dotted curves are VMD predictions, and the dashed curve is for \( Q^2 = 0 \) (which for \(^4\)He includes \( n > 2 \) rescattering terms).

at small \( x \) would be a clear signature of the onset of color opacity. For \( Q^2 \sim 5 \text{ GeV}^2 \), such an 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 \(^2\)H and \(^4\)He. We show also in this figure the expectation of the Vector Dominance model (VMD) in which a \( \rho \)-meson is produced in the first interaction and then scatters off the nucleons with a cross section similar to the \( \pi N \) cross section. In the case of a \(^4\)He target, one expects a clean minimum which is very sensitive to the amount of rescattering in Eq.(4). The investigation of the depth of the diffraction minima would allow to check another prediction of QCD, namely the large value of the real part of the production amplitude, \( \Re F / \Im F \sim 0.3 - 0.4 \).

3 Critical Assessments and Conclusions

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

References

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