Coherence Effects in Diffractive Electroproduction from Nuclei
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We argue that study of the cross section of coherent photo(electro) production of $\rho, \rho', ...$-mesons provides an effective method to probe onset of black body limit (BBL) in the soft and hard QCD interactions. We illustrate the expected features of the onset of BBL using generalized vector dominance model (GVDM). We show that this model describes very well $\rho$-meson coherent photoproduction at $6 \leq E_\gamma \leq 10$ GeV. The advantages of the process of coherent dijet production and hard diffractive processes in general for probing the onset of BBL and measuring the light-cone wave function of the photon in a hard scattering regime where decomposition over twists becomes inapplicable are explained. We argue also that the regime of color fluctuations manifests itself at intermediate energies in exclusive and semieclusive photoproduction of vector mesons and that the color transparency (CT) should reveal itself in these processes at $Q^2$ of the order of a few GeV$^2$.

1. INTRODUCTION

Studies of the coherent interactions of photons with nucleons and nuclei were one of the highlights of the strong interaction studies of the seventies, for a review see [1]. New fundamental questions to be investigated in the coherent processes are how interactions depend on the type of the projectile with increase of the size/thickness of the target and how to measure various components of the light cone wave function of the photon. Several regimes appear possible. In the case of a hadronic projectile (proton, pion, etc) high-energy interactions with the nucleus rather rapidly approach a black body limit in which the total cross section of the interaction is equal to $2\pi R_A^2$. Another extreme limit is the interaction of small size projectiles (or wave packages). In this case in a wide range of high energies the system remains frozen during the passage through the nucleus and the regime of color transparency is reached in which the interaction of the small size projectile with a nucleus is rather weak. The amplitude of interactions is proportional to the product of the matrix element of the two dimensional Laplace operator between the light-cone wave functions of projectile and hadronic final state and the gluon density of the nucleus which is somewhat smaller than the sum of the nucleon gluon densities due to the leading twist nuclear shadowing. However the cross section rapidly grows with energy reflecting
the fast increase of the gluon densities at small $x$ and large $Q^2$. Then the interaction may ultimately reach the black limit from the perturbative domain corresponding to quite different pQCD dynamics, in particular, it could be reached already at $x \geq 10^{-3}$ where $\ln x$ effects are a small correction. The BBL for the interaction of the small size dipoles with heavy nuclei represents a new regime of interactions when the leading twist approximation and therefore the whole notion of the parton distributions becomes inapplicable for the description of hard QCD processes in the small $x$ regime. Obviously there should also exist many cases when the projectile represents a superposition of configurations of different sizes that leads to fluctuations of the interaction strength. In this respect interactions of real and virtual photons with heavy nuclei provide unique opportunities since the photon wave function contains both the hadron-like configurations (vector meson dominance) and the direct photon configurations (small $q\bar{q}$ components). The important advantage of the photon is that at high energies the BBL is manifested in diffraction into a multitude of the hadronic final states (elastic diffraction $\gamma \rightarrow \gamma$ is negligible) while in the hadron case only elastic diffraction survives in the BBL and details of the dynamics leading to this regime remain hidden. Spectacular manifestations of BBL in (virtual) photon diffraction include strong enhancement of the large mass tail of the diffractive spectrum as compared to the expectations of the triple Pomeron limit, large cross section of the high $p_t$ dijet production \cite{2}. Investigation of the coherent diffraction in BBL would allow to perform unique measurements of various components of the light cone wave function of the photon, providing a much more detailed information than similar measurements in the regime where leading twist dominates.

In preQCD time V.Gribov \cite{3} explored the complete absorption of hadrons by heavy nucleus to calculate the total cross section of photo(electro)production processes off heavy nuclei through the hadron polarization operator for the photon. The distinctive feature of Gribov’s approach is that the contribution of large masses in the wave function of projectile photon (a direct photon contribution) is not suppressed. Consequently, the photon with energy $q_0 = \omega$, interacts with a nucleus with the total cross section $\sigma_{\gamma A}^{tot} \propto 2\pi R_A^2 \alpha_{em} \ln (2q_0/R_A m_n^2)$ for $A \gg 1$. This expression grossly violates expectations of the Bjorken scaling for the $Q^2$ dependence of $\sigma_{\gamma A}^{tot}$ and is qualitatively different from the hadron case where $\sigma_{h A}^{tot} \approx 2\pi R_A^2$. To overcome this puzzle J.Bjorken suggested a long time ago the aligned jet model in which only $q\bar{q}$ pairs with small $p_t$ can interact while high $p_t$ configurations in the photon wave function remain sterile\cite{4}. Existence of sterile states has been explained later as due to the color transparency phenomenon \cite{5}. More recently it was understood that some states which behave as sterile at moderate energies, interact at high enough energies with a hadron target with cross sections comparable to that for soft QCD phenomena \cite{6}. Thus the Gribov’s assumptions are justified in QCD for the interaction of a range of hadronic components of the photon wave function with heavy nucleus target. At the same time even at small $x$ the color transparency still survives for some components and one needs smaller $x$ to reach the BBL than that studied so far experimentally in ep collisions. It is worth emphasizing that the hypothesis of BBL corresponds to the assumption that at sufficiently small $x$ partons with large virtuality interact with heavy nuclei without any suppression with a cross sections $\approx 2\pi R_A^2$. Namely this feature of the BBL is responsible for the gross violation of the Bjorken scaling and for the above mentioned qualitative difference of the energy dependence of $\sigma_{\gamma A}^{tot}$ and $\sigma_{h A}^{tot}$. In preQCD time V.Gribov \cite{3} explored the complete absorption of hadrons by heavy nucleus to calculate the total cross section of photo(electro)production processes off heavy nuclei through the hadron polarization operator for the photon. The distinctive feature of Gribov’s approach is that the contribution of large masses in the wave function of projectile photon (a direct photon contribution) is not suppressed. Consequently, the photon with energy $q_0 = \omega$, interacts with a nucleus with the total cross section $\sigma_{\gamma A}^{tot} \propto 2\pi R_A^2 \alpha_{em} \ln (2q_0/R_A m_n^2)$ for $A \gg 1$. This expression grossly violates expectations of the Bjorken scaling for the $Q^2$ dependence of $\sigma_{\gamma A}^{tot}$ and is qualitatively different from the hadron case where $\sigma_{h A}^{tot} \approx 2\pi R_A^2$. To overcome this puzzle J.Bjorken suggested a long time ago the aligned jet model in which only $q\bar{q}$ pairs with small $p_t$ can interact while high $p_t$ configurations in the photon wave function remain sterile\cite{4}. Existence of sterile states has been explained later as due to the color transparency phenomenon \cite{5}. More recently it was understood that some states which behave as sterile at moderate energies, interact at high enough energies with a hadron target with cross sections comparable to that for soft QCD phenomena \cite{6}. Thus the Gribov’s assumptions are justified in QCD for the interaction of a range of hadronic components of the photon wave function with heavy nucleus target. At the same time even at small $x$ the color transparency still survives for some components and one needs smaller $x$ to reach the BBL than that studied so far experimentally in ep collisions. It is worth emphasizing that the hypothesis of BBL corresponds to the assumption that at sufficiently small $x$ partons with large virtuality interact with heavy nuclei without any suppression with a cross sections $\approx 2\pi R_A^2$. Namely this feature of the BBL is responsible for the gross violation of the Bjorken scaling and for the above mentioned qualitative difference of the energy dependence of $\sigma_{\gamma A}^{tot}$ and $\sigma_{h A}^{tot}$.
In this talk we summarize our recent studies of the various regimes of the coherent photo/electro production off nuclei [2, 7, 8]: the onset of the BBL regime, phenomenon of color transparency and perturbative color opacity related to the leading twist nuclear gluon shadowing, and the pattern of soft QCD phenomena in the proximity to the black body limit. We find that the onset of color fluctuations occurs in the photoproduction, while the onset of the color transparency in the exclusive electroproduction is expected already at intermediate energies with increase of $Q^2$.

2. VECTOR MESON PRODUCTION OFF NUCLEI IN THE GENERALIZED VECTOR DOMINANCE MODEL

We have used generalized vector dominance model (GVDM) [3, 9] to describe coherent photoproduction of hadronic states of $M \leq 2$ GeV off nuclei and consider the onset of BBL in the soft regime. The main ambiguity in generalizing the vector dominance model is the issue of nondiagonal transitions where a photon initially converts into one vector state $V_1$ which through diffractive interactions with a nucleon converts into another state $V_2$. Such amplitude interferes with the process of direct production of $V_2$. The importance of the nondiagonal transitions could be justified on the basis of the interpretation of the early Bjorken scaling for moderately small $x \sim 10^{-2}$ as due to the color transparency phenomenon - presence in the virtual photon of hadron type and point-like type configurations [5]. These amplitudes are also crucial for ensuring a quantitative matching with perturbative QCD regime for $Q^2 \leq \text{few GeV}^2$ [10]. Hence it is reasonable to use GVDM for the modeling of the production of the light states off nuclei.

The amplitude of the vector meson production off a nucleon can be written within the GVDM as

$$A(\gamma + N \rightarrow V_j + N) = \sum_i e f_{V_i} A(V_i + N \rightarrow V_j + N), \quad (1)$$

where $f_{V_i}$ are expressed through the width of the $V_i \rightarrow e^+e^-$ decay. In the case of nuclei calculation of the vector meson production amplitude within the Glauber approximation requires taking into account both the nondiagonal transitions due to the transition of the photon to a different meson $V'$ in the vertex $\gamma \rightarrow V'$ and due to change of the meson in multiple rescatterings like $\gamma \rightarrow V \rightarrow V' \rightarrow V$. This physics is equivalent to inelastic shadowing phenomenon familiar from hadron-nucleus scattering [12]. The Glauber model for the description of these processes is well known, see e.g. [11]. In Ref. [11] the simplest nondiagonal model was considered with two states $\rho$ and $\rho'$ which have the same diagonal amplitudes of scattering off a nucleon and the fixed ratio of coupling constants: $f_{\rho'}/f_{\rho} = \sqrt{3}$, while the ratio of the nondiagonal and diagonal amplitudes $A(\rho + N \rightarrow \rho' + N)/A(\rho + N \rightarrow \rho + N) = -\epsilon$, and the value $\sigma_{\rho N}^{tot}$ were found from the fit to the forward $\gamma + A \rightarrow \rho + A$ cross sections measured at $\omega_\gamma = 6.1, 6.6$ and 8.8 GeV[13]. This model with reasonable values of $\sigma_{\rho N}$ and $\epsilon$ allowed to bring the value of $f_{\rho}$ determined from the photoproduction of $\rho$-mesons off protons at assumption of approximate equality

\footnote{In our calculation we neglect the triple Pomeron contribution which is present at high energies. This contribution though noticeable for the scattering off the lightest nuclei becomes a very small correction for the scattering of heavy nuclei due the strongly absorptive nature of interaction at the central impact parameters.}
of the cross sections of $\rho - N$ and $\pi - N$ interactions into a good agreement with the value extracted from the $e^+e^-$ data thus removing a long standing 20% discrepancy between two determinations. One should emphasize here that in such VDM extension $\rho'$-meson approximates the hadron production in the interval of hadron masses $\Delta M^2 \sim 2 \text{GeV}^2$, so the values of the production cross section refer to the corresponding mass interval.

We refined this model in [8]. The dependence on the nuclear structure parameters was diminished by calculating the nuclear densities in the Hartree-Fock-Skyrme (HFS) approach which provided an excellent description of the nuclear root mean square radii and the binding energies of spherical nuclei for $A \geq 12$ and described well the nuclear transparency in the high energy $(p,2p)$ and $(e,e'p)$ reactions, see [14] and refs. therein. Next, we used in all our calculations the parametrization of [15] for the $\rho N$ amplitude which was obtained from the fit to the experimental data on photoproduction off the proton target. The value of $\epsilon$ was fixed at 0.18 to ensure the best fit of the measured differential cross section of the $\rho$-meson photoproduction off lead at $\omega_\gamma = 6.2 \text{GeV}$ and $p_t^2 = 0.001 \text{GeV}^2$. With all parameters fixed we calculated the differential cross sections of $\rho$-production off nuclei and found a good agreement with all available data [13], see Fig.1 and a detailed comparison in [8]. In difference from [11] we do not find it necessary to increase the value of $\epsilon$ by about 30% when the photon energy grows from 6 GeV to 8.8 GeV. As far as we know previously this important check of the Glauber model predictions in the vector meson production off $A > 2$ nuclei (including the t-dependence of the cross section) has never been performed in such a self-consistent way. In view of a good agreement of the model with the data on $\rho$-meson production in the low energy domain we used this model to consider the $\rho$ meson photoproduction at higher energies of photons. The increase of the coherence length with the photon energy leads to a qualitative difference in the energy dependence of the coherent vector meson production off light and heavy nuclei (Fig. 2) and to a change of the $A$-dependence for the ratio of the forward $\rho'$ and $\rho$-meson production cross sections between $\omega_\gamma \sim 10$ GeV and $\omega_\gamma \sim 40$ GeV (Fig.2). The observed pattern reflects the difference of the coherence lengths of the $\rho$-meson and a heavier $\rho'$-meson which is important for the intermediate photon energies $\leq 30$ GeV. The corrections due to nondiagonal transitions are relatively small ($\sim 15\%$) for the case of $\rho$ production off a nuclei. As a result we find that the GVD cross section is close to the one calculated in the VD model for heavy nuclei as well. Situation is much more interesting for $\rho'$ production. The cross section of $\rho'$ production off a nucleon is strongly suppressed as compared to the case when the $\rho \leftrightarrow \rho'$ transitions are switched off. The extra suppression factor is $\approx 0.5$. In accordance with the general argument of Gribov the non-diagonal transitions disappear in the limit of large $A$ (black body limit) due to the condition of orthogonality of hadronic wave functions [3]. Hence we expect that in the limit of $A \to \infty$ a more or less general relation

$$\frac{d\sigma(\gamma + A \to h_1 + A)/dt}{d\sigma(\gamma + A \to h_2 + A)/dt}_{A \to \infty} = \frac{\sigma(e^+e^- \to h_1)}{\sigma(e^+e^- \to h_2)} \approx (f_2/f_1)^2$$

The value $\epsilon = 0.18$ leads to a suppression of the differential cross section of the $\rho$-photoproduction in $\gamma + p \to \rho + p$ by a factor of $(1 - \epsilon/\sqrt{3})^2 \approx 0.80$ practically coinciding with phenomenological renormalization factor $R = 0.84$ introduced in [13] to achieve the best fit of the elementary $\rho$-meson photoproduction forward cross section in the VDM which neglects mixing effects.
Figure 1. The momentum transfer distributions of the $\rho$ and $\rho'$ photoproduction at 6.6 GeV calculated in the GVDM+Glauber model.
Figure 2. The energy dependence of the $\rho$-photoproduction cross section and the $A$-dependence of the $\rho'/\rho$ photoproduction cross sections calculated in the GVDM+Glauber model.
should be fulfilled for the productions of states $h_1, h_2$ of invariant masses $M_1^2, M_2^2$ at $k_t = 0$. Indeed we have found from calculations that in the case of the coherent photoproduction off lead the nondiagonal transitions becomes strongly suppressed with increase of the photon energy. As a result the $\rho'/\rho$ ratio increases, exceeds the ratio of the $\gamma p \to Vp$ forward cross sections calculated with accounting for $\rho - \rho'$ transitions already at $\omega_\gamma \geq 50$ GeV and becomes close to the value of $f^2_{\rho}/f^2_{\rho'}$ which can be considered as the limit when one can treat the interaction with the heavy nucleus as a black one. It is worth noting here that presence of nondiagonal transitions which in terms of the formalism of the scattering eigen states [13] corresponds to the fluctuations of the values of the interaction cross sections can be even for real photon. The GVDM model discussed in the paper leads to small ($\propto 10\%$) color transparency effects at intermediate energies for the cross section of semiinclusive photoproduction processes. Really this model corresponds to the propagation of states with cross sections: $\approx \sigma(VN)(1 \pm \epsilon)$. In the case of electroproduction $\epsilon$ should be significantly larger:

$$\epsilon \approx \frac{f_\rho}{f_{\rho'}} = \sqrt{\frac{\Gamma(\rho \to e^+e^-)}{m_\rho} / \frac{\Gamma(\rho' \to e^+e^-)}{m_{\rho'}}}. $$

This equation follows from Eq.(1) where left hand side is put to 0 because cross section of elastic vector meson electroproduction rapidly decreases with $Q^2$. The presence of the CT phenomenon within the GVDM leads to a substantial modification of the pattern of the approach to BBL. With increase of $Q^2$ the nondiagonal transitions become more important leading to an enhancement of the effects discussed above. In particular found in the paper fluctuations of strengths of interaction would lead at large $Q^2$ to the color transparency phenomenon. Presence in GVDM of masses of $\rho, \rho'$ makes it unreasonable and impossible to describe all fluctuations of strengths of interaction in terms of one coherent length.

3. LARGE MASS DIFFRACTION IN THE BLACK BODY LIMIT

One of the striking features of the BBL is the suppression of nondiagonal transitions in the photon interaction with heavy nuclei [3]. Indeed in the BBL the dominant contribution to the coherent diffraction originates from “a shadow” of the fully absorptive interactions at impact parameters $b \leq R_A$ and hence the orthogonality condition is applicable. Using this argument it is easy to derive the BBL expression for the differential cross section of the production of the invariant mass $M^2$ for scattering of (virtual) photons of transverse and longitudinal polarization:

$$\frac{d\sigma(\gamma + A \rightarrow \gamma' + A)}{dtdM^2} = \frac{\alpha_{em}}{3\pi} \frac{(2\pi R_A^2)^2 \rho(M^2)}{16\pi} \frac{4}{M^2} \left| J_1(\sqrt{-tR_A}) \right|^2.$$

Here $\rho(M^2) = \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$. Hence by comparing the extracted cross section of the diffractive production of states with certain masses with the black body limit( Eq.(3)) one would be able to determine up to what masses in the photon wave function interaction remains black. Actually similar equation is valid in the BBL for the production of specific hadronic or quark-gluonic final states ($q \bar{q}, q \bar{q}g$, etc) in the case
of the coherent nuclear recoil. Thus any component of the light cone photon wf whose interaction cross section leads to BBL is measurable by selecting certain final states in the coherent processes. Onset of BBL limit for hard processes should reveal itself also in the faster increase with energy of cross sections of photoproduction of excited states comparing to that for ground state meson. It would be especially advantageous for these studies to use a set of nuclei - one medium range like Ca and another heavy one - one could remove the edge effects and use the length of about 10 fm of nuclear matter.

One especially interesting channel is diffractive dijet production by real photons. For the $\gamma A$ energies which will be available at EIC or at LHC in UPC one may expect that the BBL in the scattering off heavy nuclei would be a good approximation for the masses $M$ in the photon wave function up to few GeV. This is the domain which is described by perturbative QCD for $x \sim 10^{-3}$ for the proton targets and larger $x$ for scattering off nuclei. The condition of large longitudinal distances - small longitudinal momentum transfer will be applicable in this case up to quite large values of the produced diffractive mass. In the BBL the dominant channel of diffraction for large masses is production of two jets with the total cross section given by Eq. (3) and with a characteristic angular distribution $(1 + \cos^2 \theta)$, where $\theta$ is the c.m. angle \[ 1 \]. On the contrary in the perturbative QCD limit the diffractive dijet production except charmed jet production is strongly suppressed \[ 17, 18 \]. The suppression is due to the structure of coupling of the real photon to two gluons when calculated in the lowest order in $\alpha_s$. As a result in the real photon case hard diffraction involving light quarks is connected to production of $q\bar{q}g$ and higher states. Distribution of diffractively produced jets over invariant mass provides an important test of the onset of BBL limit. Really in the DGLAP/CT regime differential cross section of forward diffractive dijet production should be $\propto 1/M$ and be dominated by charm jet production. This behaviour is strikingly different from BBL limit expressions of \[ 4 \]. Thus the dijet photoproduction should be very sensitive to the onset of the BBL regime. We want to draw attention that $q\bar{q}$ component of the photon light-cone wf can be measured in three independent diffractive phenomena: in the BBL off the proton, in BBL off a heavy nuclei, in CT regime where the wf can be measured as a function of the interquark distance\[ 19 \]. A competing process for photoproduction of dijets off heavy nuclei is production of dijets in $\gamma - \gamma$ collisions where the second photon is provided by the Coulomb field of the nucleus. The dijets produced in this process have positive C-parity and hence this amplitude does not interfere with the amplitude of the dijet production in the $\gamma IP$ interaction which have negative C-parity. Our estimates indicate that this process will constitute a very small background over the wide range of energies \[ 8 \].

4. EXCLUSIVE MESON PRODUCTION AT LARGE $Q^2$.

The QCD factorization theorem for exclusive meson production\[ 19, 20 \] allows to express the amplitude of the production of a vector meson by a longitudinally polarized photon $\gamma_L + T \rightarrow V + T$ through the convolution of the wave function of the meson at the zero transverse separation, hard interaction block and the skewed parton density. For practical purposes a crucial question is at what $Q^2$ squeezing becomes effective. Probably the most sensitive indicator is the $t$-dependence of the meson production. The current HERA data are consistent with the prediction of \[ 20, 21 \] that the slopes of the $\rho$ and $J/\psi$
Figure 3. The $x$-dependence of the ratio of $J/\psi$ production off Pb and a nucleon. Solid line - calculation in Impulse Approximation (IA), dashed line - calculation with the diffractive PDF of Alvero et.al. [22], dot-dashed line - H1 parametrization [23] of the diffractive PDF.
production amplitudes should converge to the same value. This indicates that at small $x$ configurations much smaller than average configurations dominate for the $J/\psi$ production for all $Q^2$ and for $\rho$ for $Q^2 \geq 5 \text{ GeV}^2$. In this kinematics the factorization theorem predicts that the cross sections of coherent production of vector mesons off nuclei are proportional (up to corrections due to skewedness effects which for large $Q^2$ and small $x$ are calculable in terms of QCD evolution equation for skewed parton distributions) to the square of the gluon parton density $G_A(x, Q^2)$ at small $x$ which is screened in nuclei as compared to the nucleon. Hence, one expects the regime of color transparency for $x \geq 0.03$ where the gluon shadowing is very small/absent. At the same time at smaller $x$ one expects a gradual disappearance of color transparency \cite{19, 20} - the onset of the perturbative color opacity. As an illustration we present in Fig.3 the calculated $x$-dependence of the transparency for $J/\psi$ production based on the leading twist gluon shadowing found in \cite{24} where results for the $\Upsilon$ production are also presented.

5. CONCLUSIONS

We demonstrated that coherent diffraction off nuclei provides an effective method of probing onset of BBL regime in hard processes at small $x$. We predict a significant increase of the ratio of the yields of $\rho, \rho'$ mesons in coherent processes off heavy nuclei due to the blackening of the soft QCD interactions in which fluctuations of the interaction strength are present. An account of nondiagonal transitions leads to a prediction of a significant enhancement of production of heavier diffractive states especially production of high $p_t$ dijets. Study of these channels may allow to get an important information on the onset of the black body limit in the diffraction of real photons. We argued that the fluctuations of strengths of interactions has been observed at intermediate energies in the diffractive photoproduction of vector mesons.

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