Coherent $\rho$ and $J/\psi$ photoproduction in ultraperipheral processes with electromagnetic dissociation of heavy ions at RHIC and LHC.

V. Rebyakova  
*Petersburg State Technical University*  
*St.Petersburg, Russia*  
M. Strikman  
*Pennsylvania State University,*  
*University Park, Pennsylvania 16802, USA*  
M. Zhalov  
*Petersburg Nuclear Physics Institute, Gatchina, Russia*

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Abstract

We present predictions for the $J/\psi$ and $\rho$ meson production in the heavy ion ultraperipheral collisions (UPC) for the current energy 2.76 TeV at the LHC. Both total cross sections and cross sections with the neutron emission from one or both nuclei are presented. We also perform analysis of the RHIC $\rho$-meson photoproduction data and emphasize importance of these data to test the current model for nucleus break up in UPC.

1 Introduction

Ultraperipheral collisions at the LHC provide a fine probe for studies of the small x dynamics in much cleaner environment than strong proton - proton (nucleus) collisions. They also provide an important bridge to the future studies at the e-A colliders. A detailed study of the UPC physics was performed by the UPC study group and reported in [1]. However, all these studies were performed for the planned energy of the heavy ion collisions at the LHC $\sqrt{s}=5.52$ TeV. Hence, it is necessary to provide the predictions for the current energy $\sqrt{s}=2.76$ TeV in models, used in [1], as well as to explore long term advantages of having UPC data at two different LHC energies. Also, we receive requests from experimental groups to calculate the quantities which are more readily accessible experimentally - the
partial cross sections with dissociation of one or two nuclei with emission of a number of neutrons.

The basic expressions for the cross section of production of vector mesons in ultraperipheral collisions are given in a number of papers, see e.g. [1]:

\[
\frac{d\sigma_{A_1A_2 \to A_1A_2 V}}{dy} = n_{\gamma/A_1}(y)\sigma_{\gamma A_2 \to V A_2}(y) + n_{\gamma/A_2}(-y)\sigma_{\gamma A_1 \to V A_1}(-y).
\]

(1)

The quantity \( y = \ln \frac{2\omega}{\gamma} \) is the rapidity of the produced vector meson, and \( n_{\gamma/A}(y) \) is the flux of photons with the energy \( \omega = \gamma L q_0 \) emitted by one of nuclei (\( \gamma L \) is the Lorentz factor for colliding nuclei, and \( q_0 \) - is the photon momentum in the coordinate system of moving nucleus).

The specific feature of the ultraperipheral collisions is rather large impact parameter \( \vec{b} \) between interacting nuclei. Hence, the flux of photons, radiated by accelerated ion, can be with reasonable accuracy approximated by the equivalent photon spectrum of the point charge \( Z \), moving with velocity \( \beta = p_N/E_N \). To avoid the strong interaction of the colliding ions (which breaks coherence of the process), one has to restrict the impact parameters \( b \) of the interaction by choosing for example \( b_{\text{min}} \approx 2R_A \) or by suppressing the strong interactions by the factor \( P_S(b) = \exp[-\sigma_{NN}T_{AA}(b)] \) with

\[
T_{AA}(b) = \int_0^\infty db' \int_{-\infty}^\infty dz \rho_A(\vec{b}' - \vec{b}, z) \int_{-\infty}^\infty \rho_A(\vec{b}', z')dz'.
\]

describing overlap of colliding ions (\( \rho_A(\vec{b}, z) \) is the nuclear density normalized by the condition \( \int d^2bdz\rho(\vec{b}, z) = A \)). However, due to the large value of \( Z \) in UPC of heavy nuclei, there is a significant probability of the photon exchange with excitation of nuclei accompanied by a subsequent decay with emission of neutrons [2]. When such additional photon exchange occurs in the final state of UPC with the vector meson photoproduction, this does not destroy the coherence of photoproduction, and sum over the final state of ions gives the total coherent photoproduction cross section. On the other hand, measurements by STAR at RHIC demonstrate that, using the Zero Degree Calorimeters (ZDC) which are installed in all detectors at RHIC and LHC, it is possible to select different channels, in particular, coherent photoproduction with excitation of ions in which neutrons are emitted by one or both nuclei. One can distinguish several channels: 1n1n - emission of one neutron by each ion, XnXn - emission of several neutrons, 0n1n and 0nXn excitation and decay only of one ion. To estimate these partial cross sections, we use the model suggested in [2] where it is shown that coherent photoproduction with additional electromagnetic nucleus excitation can be calculated modifying the flux of photons by impact parameter dependent factors \( P_i(\vec{b}) \) which account for different channels (i=0n0n, 0n1n, 1n1n, 0nXn, XnXn) [3]. Hence, the final expression for the photon flux used in our calculations is

\footnote{Our thanks to S.Klein and J.Nystrand for the kindly providing their code for calculating the probabilities of electromagnetic excitation with subsequent neutron decay}
(2)

$$n_{i/\gamma}(\omega) = \frac{2\alpha Z^2}{\pi} \int_{b_{\text{min}}}^{\infty} db \frac{x^2}{b} \left[ K_1^2(x) + \frac{K_0^2(x)}{\gamma L} \right] P_S(b) P_C^i(b),$$

where $x = \frac{\omega b}{\gamma L}$, and $K_0, K_1$ are the modified Bessel functions.

We provide predictions for the light and heavy vector meson photoproduction with small transverse momenta of vector mesons. The dynamics of production of mesons, built of light quarks, and those, built of heavy quarks, is qualitatively different. Hence, we treat them separately.

## 2 Production of light vector mesons

Production of $\rho$-meson provides an important check of the modeling of the dynamics of UPC. Indeed, the cross section $\gamma + A \rightarrow \rho + A$ is well understood theoretically. Though the Gribov space-time picture of high energy process of hadron-nucleus interaction differs qualitatively from low energy Glauber picture, numerically, the Gribov-Glauber theory which includes inelastic screening effects predicts very small (on the level of few percent) deviations from the Glauber formula for hadron-nucleus scattering. An additional element of the theory in the case of the photon projectile is presence of the non-diagonal transitions $\gamma \rightarrow \rho' \rightarrow \rho$. The generalized vector dominance model combined with Glauber approach describes well the data on $\rho$ production at $E_\gamma \sim 10\text{GeV}$ without free parameters. It also predicted reasonably well absolute cross section of $\rho$ meson photoproduction for $\sqrt{s_{NN}} = 130\text{GeV}$ as measured in the UPC at RHIC. For high energy photoproduction off heavy nuclei correction to standard VDM+Glauber model due to the account for the nondiagonal transitions is about $10 \div 15\%$. Since the uncertainty (combined experimental errors due to the restricted statistics and systematics) of the experimental cross sections measured by STAR exceeds this number almost by factor two, we use the standard Glauber model formula for calculation of the cross section of coherent $\rho$ meson photoproduction in the kinematics of UPC of heavy ions at RHIC and LHC:

$$\sigma_{\gamma A \rightarrow \rho A} = \frac{d\sigma_{\gamma N \rightarrow \rho N}(t = 0)}{dt} \int_{-\infty}^{t_{\text{min}}} dt \int_{-\infty}^{\infty} dB e^{i\vec{q}_{\perp} \cdot \vec{b}} \int_{-\infty}^{\infty} dz \Theta(b, z) e^{i\vec{q}_{\parallel} \cdot \vec{z}} e^{-\frac{\sigma_{\rho N}}{z} \int \Theta(b, z') dz'} \left( \frac{M^4}{4\rho^2} \right)^2. (3)$$

Here $\vec{q}_{\perp} = t_{\perp} - t$, $-t_{\text{min}} = |\vec{q}_{\parallel}|^2 = \frac{M^4}{4\rho^2}$ is longitudinal momentum transfer in $\gamma - \rho$ transition. We also use Donnachie-Landshoff model to calculate the total $\rho N$ cross section and forward cross section of coherent $\rho$ photoproduction off the nucleon target. This model describes reasonably well the data for $\gamma p \rightarrow pp$ at energies up to $W_{\gamma p} \approx 200 \div 300\text{GeV}$ studied at HERA but can slightly overestimate the cross section at the very high

\[\text{For the recent discussion see [3]}\]
energies due to introducing the hard pomeron exchange with large intercept ($\alpha_H = 1.44$) in such soft process as coherent photoproduction of $\rho$ with small transverse momentum. Note, that we neglect the interesting effect of interference between production by left and right moving photons [9] since it gives a small correction in the cross section integrated over rapidities, $p_t$. Our calculations for $\rho$ meson photoproduction in UPC at RHIC and LHC are given in Tables [13] and Figures [13]. In Table 1 and Fig. 1 we compare cross sections obtained in the model described above with results presented by the STAR collaboration.

It is worth noting that in the STAR experiment only the (XnXn) and (1n1n) channels were measured. The $\rho$-meson were detected in the rapidity range $-1 < y < 1$ and $p_t < 150$ MeV/c. The numbers reported by experiment for the total cross sections of various channels were calculated from the measured two cross sections using the the StarLight event generator to extrapolate to the larger $|y|$ and to calculate the ratio of the cross section in different channels.

We find a reasonable agreement at lower energies but a significant discrepancy in all measured partial cross sections at $\sqrt{s_{NN}} = 200$ GeV.

| $\sqrt{s_{NN}}$ (GeV) | UPC | 62.4 | 130 | 200 |
|-----------------------|-----|------|-----|-----|
|                       | AuAu|      |     |     |
| $\sigma_{\text{coherent}}^\rho$, mb | STAR | 137  | 520 | 910 |
|                       |     | (190±36) | (460±245) | (530±60) |
| $\sigma_{0101}^\rho$, mb | STAR | 79   | 354 | 661 |
|                       |     | (120 ±25) | (370±90) | (39±60) |
| $\sigma_{0nXn}^\rho$, mb | STAR | 45   | 132 | 198 |
|                       |     | (59.3 ±13) | (95±65) | (105±16) |
| $\sigma_{XnXn}^\rho$, mb | STAR | 13   | 34  | 51  |
|                       |     | (10.5 ±2.2) | (28.3±6.3) | (32±4.8) |
| $\sigma_{011n}^\rho$, mb | STAR | 16   | 46  | 67  |
|                       |     | -    | -   | -   |
| $\sigma_{1n1n}^\rho$, mb | STAR | 1.4  | 3.5 | 4.9 |
|                       |     | -    | (2.8±0.9) | (2.4±0.5) |

Table 1: Cross sections of the $\rho$ meson photoproduction in gold-gold UPC at RHIC calculated in the Glauber model. Numbers in brackets present results obtained by STAR collaboration from analysis of the experimental data on the gold-gold UPC studies at RHIC.

In particular, the data reported [10] do not show an increase of the cross section with increase of energy from $\sqrt{s_{NN}} = 130$ GeV to $\sqrt{s_{NN}} = 200$ GeV expected in all theoretical calculations. This is puzzling since the energy dependence of the cross section of $\rho$ photoproduction in UPC of heavy nuclei comes practically solely from the increase of the photon flux which is essentially model independent and, hence, very similar in all calculations. The
Figure 1: Comparison of the calculated cross sections for $\rho$ photoproduction in the gold-gold UPC with the STAR experimental results.
Figure 2: Calculated rapidity distributions for different channels in $\rho$ photoproduction in gold-gold UPC at RHIC.
Figure 3: Calculated rapidity distributions for different channels in $\rho$ photoproduction in lead-lead UPC at LHC.
Table 2: Comparison of the Glauber model predictions with the results of measurements by STAR for \( \rho \) meson photoproduction in gold-gold UPC at \( \sqrt{s_{NN}} = 200 \) GeV at RHIC.

| Energy   | Partial cross section, mb | \( \sigma(XnXn, |y| < 1) \) | \( \sigma(1n1n, |y| < 1) \) |
|----------|---------------------------|----------------|---------------------------|
| \( \sqrt{s_{NN}} = 130 \) GeV | Glauber model             | 18.6           | 1.87                       |
|          | STAR experiment           | 14.9 ±2.0      | 1.47 ±0.16                 |
| \( \sqrt{s_{NN}} = 200 \) GeV | Glauber model             | 25.4           | 2.4                        |
|          | STAR experiment           | 14.5 ±2.0      | 1.07 ±0.16                 |

Table 3: Cross sections of the \( \rho \) meson photoproduction in PbPb UPC at LHC calculated in the Glauber model.

| \( \sqrt{s_{NN}} \) | 2760 GeV PbPb | 5500 GeV PbPb |
|---------------------|---------------|---------------|
| UPC                 |               |               |
| \( \sigma^\rho_{\text{coherent}}, \text{mb} \) | 7023 | 9706 |
| \( \sigma^\rho_{\text{bn0n}}, \text{mb} \) | 5915 | 8309 |
| \( \sigma^\rho_{\text{bnXn}}, \text{mb} \) | 847  | 1057 |
| \( \sigma^\rho_{\text{XnXn}}, \text{mb} \) | 261  | 340  |
| \( \sigma^\rho_{\text{bn1n}}, \text{mb} \) | 260  | 306  |
| \( \sigma^\rho_{\text{bn1n}}, \text{mb} \) | 18.5 | 21   |

Cross section \( \gamma + p \to \rho + p \) is a weak function of energy in the discussed energy interval and \( \gamma + A \to \rho + A \) is expected to be an even weaker function of the incident energy due to the blackness of the interaction with heavy nuclei at small impact parameters.

One can see from the Table 2 that the measured cross sections at two energies are practically equal while the calculated ones increase by a factor \( \approx 1.3 \), which coincides with an increase of the average photon flux.

In Fig.3 we present our predictions for the rapidity distributions of the \( \rho \) photoproduction at energies \( \sqrt{s_{NN}} = 2.76 \) TeV and \( \sqrt{s_{NN}} = 5.5 \) TeV at LHC. The total cross sections are given in Table 3.

Since \( d\sigma(\gamma A \to \rho A)/dt(t = 0) \) weakly depends on energy, combined studies at several energies and at different rapidities will provide a stringent test of the dynamics of the break up of nuclei due to e.m. interactions.

Note in passing that our cross sections larger than the Starlight results since the Starlight MC code uses expression for the total cross section of hadron - nucleus interaction given by classical mechanics which in the limit of large total \( VN \) cross sections and large \( A \) differs from the Gribov-Glauber model by a factor of about two. Recently one more update of predictions for total coherent cross sections in heavy ion UPC at RHIC and LHC has been published [12]. The calculations in [12] are based on use of Color Glass...
Condensate (CGC) ideas and two versions of the color dipole model (IP-SAT [13] and IIM[14]). Comparing to the data of STAR at $\sqrt{s_{NN}} = 200$ GeV the authors found that IP-SAT model gives a larger cross section of $\rho$ photoproduction but the result with IIM model appears to be close to that of the STAR experiment. So, cross section at the LHC energies predicted with this model are considered by the authors as preferable. However, as we show in this paper, the STAR measurements at $\sqrt{s_{NN}} = 200$ GeV give the cross sections practically equal to cross sections at $\sqrt{s_{NN}} = 130$ GeV, and this doesn’t agree with reasonable energy dependence, dictated by the increase of the photon flux with increase of $\sqrt{s_{NN}}$. As a result, the cross sections of $\rho$ photoproduction in UPC at LHC, predicted in [12], appeared to be smaller than our. Note in passing that the color dipole models are usually used for description of the hard interactions. A rational to apply such a model for the description of the soft process of the $\rho$ meson exclusive photoproduction is not clear, as opposed to the use of the (generalized) vector dominance model which is theoretically well justified in this case.

3 J/$\psi$ production

The coherent production of J/$\psi$ in UPC is one of the direct ways of probing the pattern of the interaction of small color dipoles of average transverse size $\sim 0.2 \div 0.25$ fm [15]. Due to their small size, the dominant mechanism of coupling of the $c\bar{c}$ to the nucleon is through a two gluon attachment which forms a start of the gluon ladder. In the dipole approximation the cross section of $\gamma + T \to J/\psi + T$ process can be calculated in the Leading Order of PQCD [16] [17]

$$\frac{d\sigma_{\gamma T \to J/\psi T}(t = 0)}{dt} = \frac{16\Gamma_{ee} \pi^3}{3\alpha_{em} M_{J/\psi}^5} \left[ \alpha_s(\mu^2) x G_T(x, \mu^2) \right]^2$$

(4)

Here $\Gamma_{ee}$ is width of the leptonic decay of J/$\psi$ and $G_T(x, \mu^2)$ is density of gluons with fraction $x = \frac{M_{J/\psi}^2}{s_{\gamma T}}$ of momentum of the target ($s_{\gamma T}$ is the invariant energy for $\gamma - T$ scattering), and $\mu^2$ is the scale which we choose to be $\mu^2 = \frac{M_{J/\psi}^2}{4}$. Applying Eq(4) to the proton and nucleus target, one can write the cross section for the photoproduction of J/$\psi$ off the nucleus in the form

$$\sigma_{\gamma A \to VA}(\omega) = \frac{d\sigma_{\gamma N \to VN}(\omega, t_{min})}{dt} \left[ \frac{G_A(M_{J/\psi}^2, Q^2)}{G_N(M_{J/\psi}^2, Q^2)} \right]^2 \int_{t_{min}}^{t_{max}} dt \left| \int d^2 b d\mathbf{z} e^{i\mathbf{q} \cdot \mathbf{b}} e^{-|q|^2} \rho(\mathbf{b}, z) \right|^2 .$$

(5)

The key feature of the photoproduction of the hidden heavy flavor vector mesons off heavy nuclei is the gluon nuclear shadowing which is characterized by the ratio of the nuclear gluon density distribution $G_A(x, \mu^2)$ to the proton gluon distribution $G_N(x, \mu^2)$.
Figure 4: Calculated rapidity distributions for different channels in $J/\psi$ photoproduction in gold-gold UPC at RHIC.
Figure 5: Calculated rapidity distributions for different channels in $J/\psi$ photoproduction in lead-lead UPC at LHC.
Figure 6: Calculated rapidity distributions for (0n0n) and (0n1n) channels in $J/\psi$ photoproduction in PbPb UPC at $\sqrt{s_{NN}} = 2.76$ TeV. Shaded area shows uncertainty in accounting for the gluon nuclear shadowing. Left and right curves demonstrate one-side contributions.
Figure 7: Distributions on the transverse momentum transfer in coherent and incoherent $J/\psi$ photoproduction in PbPb UPC at $\sqrt{s_{NN}} = 2.76$ TeV.
The $G_A/G_N$ ratio can be calculated within the theory of leading twist nuclear shadowing [19] (see [20] for details of the model and references) developed on the base of the Gribov’s theory of inelastic shadowing, Collins’s factorization theorem for hard diffraction and the DGLAP evolution equations. This model uses, as an input, nucleon diffractive parton distribution functions (pdf) which are available both in the NLO and in LO. In our study we select LO nucleon pdfs which give a reasonable description of the energy dependence of the elementary cross section. Also, we use the LO gluon density in proton $G_N(x, \mu = 2.5 GeV^2)$, recently found [18] by the Durham-PNPI group in the range $10^{-4} < x < 10^{-2}$ from the fit of cross section, given by (Eq.4), to the HERA experimental data on $\gamma + p \rightarrow J/\psi + p$.

The results of calculations are presented in Figs. 4 - 6 and in the Table 4. Since the estimate of shadowing is based on the parton distribution functions determined from the data, there is some uncertainty related to the experimental errors. In Fig. 6 we show how this uncertainty influence our estimates of the cross sections.

Comparing our results with those of StarLight and [12], we find for $J/\psi$ photoproduction at LHC smaller cross sections. This is due to the accounting for the Leading Twist gluon shadowing which was not included in StarLight. The calculation of [12] included only higher twist shadowing in the color dipole model which is known to be much smaller than the leading twist shadowing in a wide range of $x$, see [22] for detailed comparison of the shadowing in the leading twist approximation and in the color dipole model.

As we mentioned before, the coherent scattering is determined by the sum of lower and higher energy contributions. This makes it difficult to separate these contributions at any rapidity, except for $y = 0$ where they are equal. One would like to determine the coherent cross section in as wide range of $\gamma A$ energies as possible, with higher energies allowing to probe the gluon density at lower $x$. For example, in PbPb UPC at $\sqrt{s_{NN}} = 2.76$ TeV and rapidity of produced $J/\psi$ $y \approx 0$ the corresponding $x \approx 10^{-3}$, while, if one could extract contribution due to the higher energy photon to the the cross section of production $J/\psi$ with $y \approx 2$, it would be possible to extract gluon density at $x \approx 1.5 \cdot 10^{-4}$. However, due to the rapid drop of the flux of photons with higher energy, this contribution is significantly lower than the cross section from the low energy photons (see Fig.6) which is determined by the gluon density at $x \approx 10^{-2}$. It was argued [2] that measurement of the process of photoproduction with additional photon exchange enhances the contribution from the higher energy photons. We would like to emphasize that measuring at the same $\sqrt{s_{NN}}$ two or more channels with $J/\psi$ at fixed rapidity, for example, (0n1n) and (0n0n) or any other, one can easily separate high and low energy contributions, provided that the fluxes of photons modified by accounting for the neutron decay are calculated with reasonable accuracy. These fluxes and the procedure in whole can be tested in study of $\rho$ photoproduction in PbPb UPC since the cross section of $\rho$ photoproduction off nuclear target weakly depends on energy and can be calculated in the Glauber model. Also we would like to note that contribution of the incoherent photoproduction in the UPC at LHC which are usually accompanied by neutrons [21] to the coherent cross section with detection
Table 4: Cross sections of $J/\psi$ photoproduction in gold-gold UPC at RHIC and PbPb UPC at LHC calculated in the leading order LT shadowing model.

| $\sqrt{s}_{NN}$ | AuAu 130GeV | AuAu 200GeV | PbPb 2760GeV | PbPb 5500 GeV |
|----------------|-------------|-------------|--------------|--------------|
| $\sigma_{\text{tot}}, \mu b$ | 24 | 137 | 9281 | 15836 |
| $\sigma_{0n0n}, \mu b$ | 10.1 | 68 | 7044 | 12376 |
| $\sigma_{0nXn}, \mu b$ | 10.2 | 52 | 1689 | 2584 |
| $\sigma_{XnXn}, \mu b$ | 3.7 | 17 | 548 | 876 |
| $\sigma_{0n1n}, \mu b$ | 3.25 | 16.8 | 512 | 739 |
| $\sigma_{1n1n}, \mu b$ | 0.35 | 1.6 | 39 | 54 |

of neutrons will be very small if one uses the low $p_t$ of produced $J/\psi$ (see Fig. 7).

If the measurements are done at two energies $\sqrt{s} = 2.76$ TeV and $\sqrt{s} = 5.52$ TeV a simultaneous analysis of two data sets will allow to extend model independent determination of nuclear ratio to $x$ at least a factor of two smaller than in $y = 0$ at $\sqrt{s} = 5.52$ TeV.

4 Conclusions

The studies of the $J/\psi$ production in the heavy ion UPC at the LHC will allow to measure coherent photoproduction cross section down to $x \approx 10^{-4}$ using the channels without nucleus break up which dominate at the LHC energies. A cross check will be possible using channels with dissociation of nuclei. However, this would require sorting out situation with the $\rho$-meson production at the RHIC energies. This requires both further experimental studies at RHIC and LHC as well as further theoretical studies.

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