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Neutron tagging of quasielastic J/ψ photoproduction off nucleus in ultraperipheral heavy ion collisions at RHIC energies

M. Strikman [a], M. Tverskoy [b], M. Zhalov [b]

[a] *Department of Physics, Pennsylvania State University, University Park, PA 16802, USA*
[b] *St. Petersburg Nuclear Physics Institute, Gatchina 188300, Russia*

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Abstract

We compare the coherent and quasielastic J/ψ photoproduction in the peripheral heavy ion collisions in kinematics of Relativistic Heavy Ion Collider (RHIC) at $\sqrt{s_{NN}} = 200$ GeV. Our improved estimate of the total coherent cross section is a factor of two smaller than the earlier ones. We find that the counting rate of quasielastic J/ψ photoproduction tagged by neutrons emitted due to cascading of the recoiled nucleon within the residual nucleus exceeds the rate of the coherent events. We argue that measurements of this process can be used to learn about the dynamics of color dipole–nucleon interactions in nuclei in the wide effective range of energies of γA interactions.

The impressive program of the studies of hard high energy electroweak interactions with nucleons is being performed at HERA for about ten years. Unfortunately, it will not be followed by the corresponding program of studies of the interactions with nuclei in the near future.

In this situation it is important to continue at least some of these studies (see for review Refs. [1,2]) using possibilities which become available at the heavy ion colliders due to ultraperipheral collisions (UPC) of nuclei in which nuclei pass at impact parameters $b > 2R_A$.

Recent observation of coherent ρ-meson production in the UPC of nuclei at RHIC [3] has demonstrated the feasibility of this approach. The measured cross section of the coherent ρ meson photoproduction agrees well with theoretical predictions (see, for example, Refs. [4–6]). It was also demonstrated experimentally that a noticeable fraction of the coherent events is followed by the Coulomb induced neutron emission. So far, both the experimental and the theoretical studies were focusing on coherent production of vector mesons (VM). Though the coherent production of the vector mesons is rather easy to identify by select-

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E-mail address: strikman@phys.psu.edu (M. Strikman).

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ing events where transverse momentum of the VM is sufficiently small, $\leqslant \sqrt{3}/R_A$, it is very difficult to determine whether a left or right moving nucleus was the source of the photon which converted into a VM. Since the photon flux strongly decreases with an increase of the photon energy, this makes it very difficult to study the photoproduction of the VM at $s_{\gamma N} > m_V\sqrt{s_{NN}}$. The only currently proposed idea in this direction [7] is to use the properties of the final states—the pattern of the emission of the neutrons due to one-side or mutual dissociation of the nuclei by their Coulomb fields. Since the breakup happens at smaller impact parameters, one could in principle combine different data sets to separate the higher energy and lower energy contributions. The effect is rather weak for the RHIC energies to be of practical use, but may be promising for the LHC.

At the same time, there exists another process of vector meson production with comparable cross section which is sensitive to the dynamics of the VM interaction within the nuclear medium—quasielastic (QE) production, $\gamma + A \to V + A'$. The A-dependence of this process varies from $\propto A$ for the case, when absorption is small, to $A^{1/3}$ for the case of strong absorption (only scattering off the nuclear rim contributes in this case). Thus, the sensitivity to the change of σ_{VN} is as large $\propto A^{2/3}$ as for the coherent process for which cross section integrated over t is $\propto \sigma^2_{\text{tot}}(VA)/R^2_A$.[1]

An important feature of most of the current detectors is that it is much easier to trigger on the VM production if it is accompanied by a breakup of at least one of the nuclei, leading to production of one or more neutrons with energy $\sim E_N \approx 0.5\sqrt{s_{NN}}$ which hit a zero degree calorimeter (ZDC). The current measurements and numerical estimates indicate that at the RHIC energies such excitations in the case of, say, coherent J/ψ production occur with a probability $\sim$ (50–60)% [7]. At the same time, the removal of a nucleon from a heavy nucleus in the quasielastic process should lead to a significant breakup of the nucleus, resulting in the production of neutrons with a probability of the order one. Hence, the rates of detection of the quasielastic and coherent processes in heavy ion scattering at RHIC should be comparable.

An attractive and useful feature of quasielastic photoproduction in peripheral heavy ion UPC at colliders is that the neutrons are emitted from the nucleus interacting with the photon. Then it will be straightforward to resolve an ambiguity between left and right moving emitters in this case. As a result, we suggest that, provided the detectors have a good acceptance for rapidities away from $y = 0$, it would be possible to study the dynamics of VM production off nuclei in the QE scattering in the significantly wider energy range at RHIC and especially at LHC than for the coherent case.

In this Letter we start an investigation of the characteristics of the QE processes relevant for their identification in UPC. As a starting point, we will use the process of the J/ψ photoproduction at RHIC energies. There are several reasons for this choice. Firstly, at the RHIC energies effective J/ψ absorption in the nuclear medium is small, so it is reasonable to use for the initial modeling the impulse approximation for the interaction of the photon with individual nucleons for the process of the incoherent J/ψ photoproduction off nucleus. Secondly, this process is currently being analyzed by the PHENIX Collaboration [8]. On top of this, mechanisms of the J/ψ photoproduction and interaction of the J/ψ with nucleons have been the subject of theoretical and experimental studies for a long time. Experimental studies of J/ψ photo and electroproduction at HERA [9] found that many features of this process are correctly predicted by perturbative QCD, in particular, the energy dependence of the cross section, weak Q^2 and energy dependence of the slope parameter of the electroproduction amplitude. Also, the QCD inspired models describe reasonably the absolute cross section of the process. However very little is known [10,11] about dependence of the coherent and quasielastic photoproduction of J/ψ on atomic number which provide sensitive tests of the color transparency effects in the propagation of small color dipoles through the nuclear media.

The cross section of J/ψ coherent production in UPC at RHIC and LHC was estimated in a number of papers (see, for example, Refs. [4,6,12]) with the conclusion that the rates should be sufficiently high to study the process.

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[1] Note that even small objects can be absorbed strongly at sufficiently high energies due to the leading twist shadowing and due to the higher twist effects.

We will argue below that the incoherent J/ψ photoproduction followed by nuclear breakup initiated by the recoiled nucleon has a tagging efficiency due to the registering the neutrons by ZDC close to one. As a result, we find that the counting rate for this process at RHIC should be about the same or even exceed the rates for coherent processes with the nuclear breakup by the Coulomb field. We will demonstrate that, on average, about four neutrons should be emitted after the knocked out nucleon escapes though the nuclear media. Consequently, analysing the ZDC signals it will be possible to single out QE events and identify which of the nuclei was the source of the photons that provides a possibility to measure the energy dependence of J/ψ production up to significantly higher energies.

The purpose of this Letter is to provide a quantitative proof of this idea. In the following publications we will address a number of issues related to combining effects of nuclear breakup due to the QE and the Coulomb mechanisms, attenuation effects, etc.

The cross section of the photoproduction of J/ψ in the peripheral ion–ion collisions in the well-known Weizsacker–Williams approximation [13] is given by expression

$$\frac{d\sigma(AA \to VAX)}{dydt} = N_\gamma(y)\frac{d\sigma_{\gamma A\to VX}(y,t)}{dt} + N_\gamma(-y)\frac{d\sigma_{\gamma A\to VX}(-y,t)}{dt}, \tag{1}$$

where $y = \ln\frac{2\omega}{M_V}$ is the rapidity and $N_\gamma(y)$ is the flux of the equivalent photons produced by the Coulomb field of the relativistic heavy ion. This quantity can be calculated with a reasonable precision using a simple expression [1]

$$N(y) = \frac{Z^2\alpha}{\pi^2}\int d^2b\, \Gamma_{AA}(\vec{b})\frac{1}{b^2}X^2 \times \left[K_1^2(X) + \frac{1}{\gamma}K_0^2(X)\right]. \tag{2}$$

Here $K_0(X)$ and $K_1(X)$ are modified Bessel functions with argument $X = \frac{bM_V e^y}{2\gamma}$, γ is the Lorentz factor and $\vec{b}$ is the impact parameter. The Glauber profile factor,

$$\Gamma_{AA}(\vec{b}) = \exp\left(-\sigma_{NN}\int_{-\infty}^{\infty} dz\int d^2b_1\,\rho_A(z,\vec{b}_1) \times \rho_A(z,\vec{b}-\vec{b}_1)\right), \tag{3}$$

accounts for the inelastic strong interactions of the nuclei at impact parameters $b \leqslant 2R_A$ and, hence, suppresses the corresponding contribution to the vector meson photoproduction.

As a first step we consider the incoherent J/ψ photoproduction off the nucleus, neglecting the initial and final state interaction of the $c\bar{c}$ wave package which evolves into a quarkonium with the residual nucleus. According to our estimate in Ref. [14] the total $J/\psi\ N$ cross section is on the level of 3.5 ± 0.5 mb. A similar number comes from a consideration of the $q\bar{q}$–nucleon cross section for the energies of RHIC and transverse sizes characteristic for J/ψ photoproduction. Hence, use of the impulse approximation seems to be quite reasonable. At the same time the dependence of the elementary amplitude $\gamma + N \to J/\psi + N$ on the momentum transfer t is rather flat—the slope parameter $B_{J/\psi N} \sim 4\ \text{GeV}^{-2}$. Hence, the effective range of t in quasielastic production can be rather large, up to $1\ \text{GeV}^2$, as compared to the case of coherent J/ψ photoproduction off nuclei where the relevant values of t are $-t \leqslant 0.015\ \text{GeV}^2$ due to suppression of higher momentum transfer by the nuclear formfactor. The probability to break up the nucleus by the recoiled nucleon with momentum $p_N \approx \sqrt{(-t)} \leqslant 1$ GeV in the nucleus rest frame is high enough because of the large total nucleon–nucleon cross section for this range of momenta.

To characterize the process of the interaction of the recoiled nucleon with the residual nucleus in the reaction $N + (A-1) \to C_i + kn$ we introduce the excitation function $\Phi_{C_i,kn}(p_N)$ which is the probability to produce exactly k neutrons and any number of the charged fragments C_i. The excitation function $\Phi_{C_i,kn}(p_N)$ has been calculated using the Monte Carlo code accounting for the cascading of the nucleon within the nuclear medium followed by the evaporation of nucleons and fragments. In Ref. [15] we used the same Monte Carlo code to analyze the neutron production in the fixed target experiment at FNAL (E665)

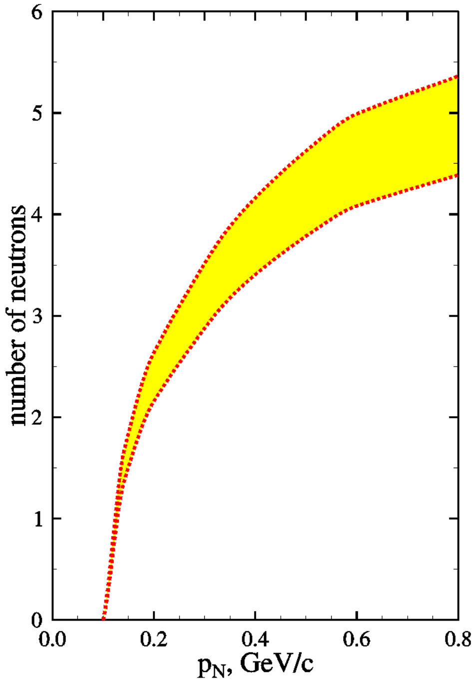

Fig. 1. Average number of neutrons for the incoherent production of J/ψ in UPC of Au at RHIC as a function of the recoiled nucleon momentum $p_N = \sqrt{-t}$. The band indicates our estimate of the uncertainties of the MC calculation.

which studied soft neutron production in deep inelastic scattering of muons off lead. We obtained a good description of these data [16] as well as of the various data on production of neutrons in the proton–nucleus scattering at intermediate energies. The dependence of the average number of the emitted neutrons from the residual nucleus on the momentum of the recoiled nucleons is shown in Fig. 1. One can see from the figure that for typical J/ψ transverse momentum in the QE process $\sim B_{J/\psi N}^{-1/2} \sim 0.5\ \mathrm{GeV}/c$ in average about four neutrons per event should be emitted.

The cross section of the incoherent J/ψ photoproduction accompanied by the breakup of the residual nucleus is given by the expression

$$\frac{d\sigma}{dt\,dy} = A\frac{d\sigma_{\gamma+N\to J/\psi+N}(s,t)}{dt}\sum_{C_i,k}\Phi_{C_i,kn}(p_N), \tag{4}$$

where $s = 2\gamma m_N m_{J/\psi}\exp(y)$ is the photon–nucleon center-of-mass energy and the momentum transfer $-t = m_{J/\psi}^4 m_N^2/s^2 + t_\perp$.

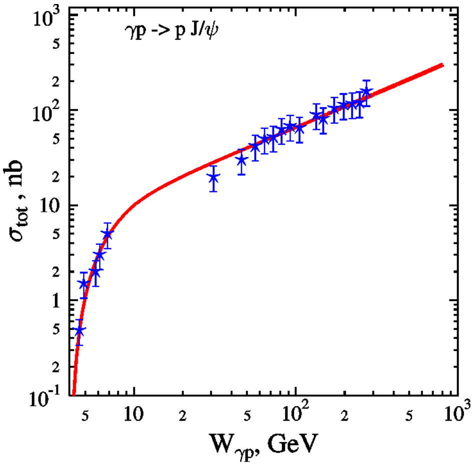

Fig. 2. The total cross section of the $\gamma + p \to J/\psi + p$ production as a function of the $W_{\gamma p} = \sqrt{s_{\gamma p}}$. Experimental data from [17], solid line—fit to the data using the parametrization of cross section given by Eq. (5).

The cross section of photoproduction off nucleon was parametrized by the QCD motivated formula with free parameters fitted to the existing data [17]:

$$\begin{aligned}\frac{d\sigma_{\gamma N\to J/\psi N}(s,t)}{dt} &= 280\left[1-\frac{(m_{J/\psi}+m_N)^2}{s}\right]^{1.5}\left(\frac{s}{10\,000}\right)^{0.415}\\ &\quad\times\left[\Theta(s_0-s)\left[1-\frac{t}{t_0}\right]^{-4}\right.\\ &\quad\left.+\,\Theta(s-s_0)\exp(B_{J/\psi}t)\right].\end{aligned} \tag{5}$$

Here $t_0 = 1\ \mathrm{GeV}^2$ and the slope parameter for $J/\psi N$ scattering was parametrized by the expression,

$$B_{J/\psi} = 3.1 + 0.25\log_{10}(s/s_0),$$

with $s_0 = 100\ \mathrm{GeV}^2$. This fit (Fig. 2) gives a good description of all existing data. At the same time, we found that the low energy extrapolation of the Landshoff–Donnachie parametrization of the J/ψ N cross section [18] which we have used in our previous paper [12] to estimate coherent J/ψ photoproduction off nuclei in the UPC of heavy ions significantly overestimates the value of cross section at rapidities away from zero. Moreover, from our study of the low energy coherent photoproduction of J/ψ off nuclear targets [14] we find that it is more reasonable to use a larger

Table 1
Total cross sections of coherent and incoherent J/ψ photoproduction calculated in the impulse and the Glauber approximations for $\mathrm{Au}+\mathrm{Au}\to \mathrm{Au}+X+J/\psi$ in UPC at RHIC

Approximation	Coherent (μb)	Incoherent (μb)	Incoherent $0n$, $0n$ (μb)	Incoherent $0n$, Xn (μb)
Impulse	212	264	38	215
Glauber	168	177	25.5	144

effective $J/\psi\ N$ cross section in the region of relatively large $x \equiv M^2_{J/\psi}/s \geqslant 0.01$ relevant for RHIC: $\sigma_{\mathrm{eff}}(x \geqslant 0.015) = 3$ mb compared to the value 1 mb used in [12]. In total, these modifications resulted in the reduction of the cross section of the coherent J/ψ photoproduction off gold in the kinematics of RHIC by the factor ≈ 2. To estimate the final state interaction of the produced J/ψ with the residual nucleus in the incoherent process we have used simple Glauber type model approximation for the probability that there is exactly one elastic rescattering and no inelastic interactions

$$\sigma_{\mathrm{inc}}^{\gamma A\to J/\psi A} = 2\pi\sigma(\gamma N\to J/\psi N) \times \int_0^\infty b\,db \int_{-\infty}^{\infty} dz\,\rho(\vec{b},z)\exp\bigl[-\sigma_{\mathrm{tot}}^{J/\psi N}T(\vec{b})\bigr]. \tag{6}$$

Here $T(\vec{b}) = \int_{-\infty}^{\infty}\rho(\vec{b},z)\,dz$ is the nuclear profile function and $\sigma_{\mathrm{tot}}^{J/\psi N}$ is the effective quarkonium–nucleon total cross section which we have taken to be equal to about 3 mb.[2] The coherent and incoherent J/ψ photoproduction cross sections in UPC, integrated over rapidity and momentum transfer for kinematics of RHIC, are given in Table 1. In this table we also present the partial cross sections of quasi-elastic J/ψ production without any emitted neutrons in both direction of the collision indexed by $(0n, 0n)$ and the cross sections with nuclear breakup with the number $X \geqslant 1$ neutrons in one of two directions $(0n, Xn)$.

The rapidity distributions for the coherent and quasielastic J/ψ photoproduction, integrated over the momentum transfer, are shown in Fig. 3 for several values of J/ψ–nucleon cross section to illustrate sensitivity of these cross sections to the strength of J/ψ–N interaction. The coherent distribution is more narrow due to suppression by the nuclear formfactor in the region where the longitudinal transferred momentum $p_z = \frac{m^2_{J/\psi}m_N}{s}$ is still significant.

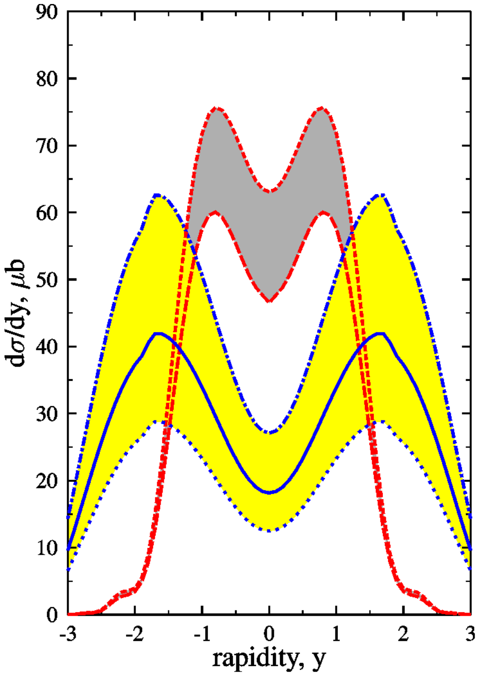

Fig. 3. The integrated over momentum transfer rapidity distributions for the J/ψ coherent photoproduction in UPC of Au ions at RHIC calculated with effective cross section for J/ψ–nucleon interaction of 3 mb (long-dashed line) and in the impulse approximation (short-dashed line). The incoherent J/ψ production cross section estimated in the Glauber model for J/ψ–nucleon cross section of 3 mb (solid line) and 6 mb (dotted line), and in the IA (dot-dashed line).

The dependence of the cross sections, integrated over rapidity, on the momentum transfer are given in Fig. 4. It is seen that one can easily discrimi-

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[2] For intermediate energies this effective cross section is likely to be substantially smaller than the genuine $J/\psi\ N$ cross section, while for very high energies situation should reverse, see discussion in [2].

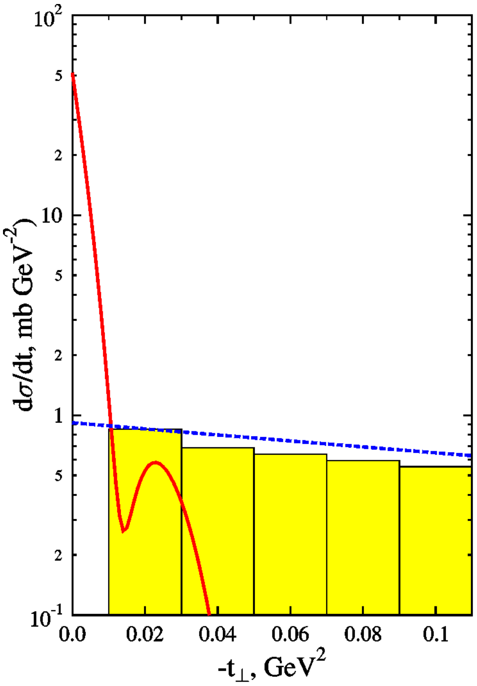

Fig. 4. Integrated over rapidity ($-3 \leqslant y \leqslant 3$) the momentum transfer distributions for the J/ψ in the coherent (solid line) and incoherent (dashed line) photoproduction in UPC of Au ions at RHIC and the cross section of the incoherent photoproduction (shadowed histogram) accompanied by neutrons.

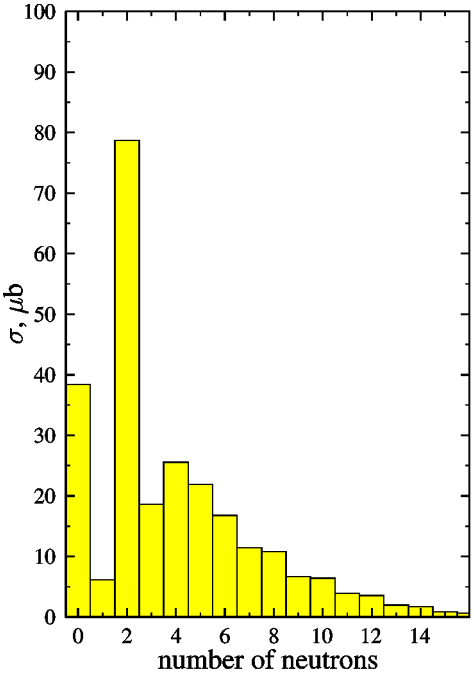

Fig. 5. The incoherent cross section for the J/ψ production in UPC of Au ions at RHIC as a function of the number of accompanied neutrons.

nate the coherent and QE events by selecting different transferred momenta. Actually, at $t \leqslant 0.01$ GeV^2 the contribution of the QE production (dashed line) is small, however, the QE mechanism dominates at higher t. The shaded histogram presents the incoherent J/ψ photoproduction followed by the neutrons, emitted due to the final state interaction of the recoiled nucleon. One can see that the QE J/ψ production is accompanied by neutrons with a probability very close to one. The only exception is the region of very small momentum transfers where the energy of the recoiled particle is insufficient to remove extra nucleons (in gold the minimal separation energy is about 5 MeV). Generally, the ratio of the cross section with emission of the one or more neutrons to the total incoherent cross section is about 0.8. The dependence of the incoherent cross section, integrated over rapidity and momentum transfer, on the number of emitted neutrons is presented in (Fig. 5). The distribution has a pronounced peak at multiplicity of neutrons $k = 2$ and the long tail up to the $k = 14$. The average number of the emitted neutrons is $\langle k_n \rangle \approx 4.5$ with $\sqrt{\sigma^2} \approx 0.68$. Emission of one neutron is strongly suppressed due to a small probability for a decay of the hole produced by the nucleon knock out to produce just one neutron and a probability $\geqslant 0.5$ for the knockout nucleon to produce a neutron while propagating through the nucleus. A distinctive feature of the neutron tagging of the incoherent J/ψ photoproduction is that it allows to determine which of the nuclei acted as a photon target since the neutrons are emitted by this nucleus. This enables one to resolve the ambiguity between photon-emitter and photon-target for a given rapidity, which is hardly possible for the coherent case (at least on the event by event basis).

Another important point is that, in the first approximation, the Coulomb field induced emission of neutrons in the coherent process does not depend on the transverse momentum of J/ψ. Hence, this mechanism can be quantified in the coherent production at small $t_\perp$ and correspondingly folded in at higher t in the QE J/ψ production.

The pattern of the neutron emission which we find in QE J/ψ production is qualitatively different from the case of the electromagnetic excitation. First, according to the prediction of Ref. [7] a large fraction of collisions ($\approx$ 50–70%) occur at RHIC energies without such excitations. Second, the largest partial channel is the emission of one neutron ($1n$), followed by a two neutron emission ($2n$) which constitutes about 35% of $1n$ events, and by a long tail with a broad and falling distribution [19]. On the other hand, in the QE mechanism the production of the two neutrons is most likely. Also, there is a different pattern of correlation between emission in two opposite cones in QE and EM mechanism. In the QE mechanism neutrons are produced only in one of two directions while in the EM mechanism simultaneous production in both directions is possible.

A more detailed analysis including both EM and QE induced neutron emission in quarkonia photoproduction in the UPC of ultrarelativistic heavy ions will be presented elsewhere.

Note also that in this discussion we neglected diffractive processes of production of J/ψ with break up of the nucleon: $\gamma + p \to J/\psi + M_X$. For relatively small masses, M_X, the products will be not detected in the central detector and, hence, the process would be attributed to the QE sample. Very little is known about this process at the energies one probes in UPC at RHIC. Based on the information at higher energies, one can guess that this process should constitute about 10–20% of the elastic production at $t \sim 0$ and have much smaller slope (at least a factor of two smaller). Correspondingly, it will further enhance the QE signal. In principle, it could be separated using the t-dependence of the QE J/ψ production, as well as the neutron signal.

In conclusion, we presented an improved estimate of the cross section of the coherent J/ψ photoproduction in UPC at kinematics of the RHIC. The total cross section is found to be about of 170 µb that is approximately by a factor of two smaller than the prediction of our previous paper [12] and of Refs. [4,6,7]. We suggested a new mechanism, the neutron tagging of the incoherent J/ψ photoproduction in the UPC of the heavy ions, which can provide a possibility of reliable selection of the events of J/ψ production by the high energy photons. The precision measurements of the discussed processes (combined with experiments to improve the knowledge of the elementary $\gamma + N \to J/\psi N$ reaction) would allow to get important information about the dynamics of J/ψ–N interaction.

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