Near-threshold $J/\psi$ photoproduction off nuclei

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Abstract

We study the $J/\psi$ photoproduction from nuclei near the kinematic threshold within the first collision model, based on the nuclear spectral function, for incoherent primary photon–nucleon charmonium creation processes. The model takes into account the final $J/\psi$ absorption, target nucleon binding and Fermi motion, the formation length of $J/\psi$ mesons as well as the effect of their nuclear mean-field potential on these processes. We calculate the $A$ dependences of the absolute and relative (transparency ratio) charmonium yields as well as its absolute and relative excitation functions within the different scenarios for the $J/\psi N$ absorption cross section, for the $J/\psi$ formation length and for $J/\psi$ in-medium modification. We demonstrate that the studied observables, on the one hand, are not practically affected by the charmonium formation length and mass shift effects and, on the other hand, they are appreciably sensitive to the genuine $J/\psi N$ absorption cross section at above threshold beam energies, which means that these observables can be useful to help determine the $J/\psi N$ absorption cross section from the comparison of the results of our calculations with the future data from the experiments in the Hall C at the upgraded up to 12 GeV CEBAF facility. We also show that the absolute and relative excitation functions for $J/\psi$ subthreshold production in $\gamma A$ reactions reveal some sensitivity to adopted in-medium modification scenarios for $J/\psi$ mesons. Therefore, such observables, measured in the subthreshold energy domain, may be an important tool to get valuable information on the charmonium in-medium properties in cold nuclear matter.
1. Introduction

The production and suppression of $J/\psi$ mesons on a nuclear targets have been intensively studied over the last thirty years, both experimentally and theoretically. Most investigations of these issues have been carried out in the field of relativistic proton–nucleus and nucleus–nucleus collisions (see, e.g., [1–28]). The main goal of the studies in this field was to get valuable information about a possible restoration of chiral symmetry above some critical temperature and density accompanied by the phase transition from composite hadrons to a quark-gluon plasma. And the suppression of $J/\psi$ yield observed in heavy–ion collisions at SPS and RHIC is recognized, beginning from the work [29], as one of the most promising signals of the transition of ordinary hadronic matter to a deconfined phase of quarks and gluons. In addition to the above prominent prospect, in-medium properties of charmonium states, the strength of the inelastic $J/\psi$–nucleon interaction are of further interest in view both of the feasibility of an experimental observation of the one of the new kinds of exotic nuclei–narrow bound $J/\psi$–nucleus states [30] and of gaining more insight into the dynamics of low-energy QCD in the charm and hidden charm sectors [31, 32]. What concerns the experimental situation, up to now a wide variety of high statistics $J/\psi$ data samples have been collected in proton–nucleus and heavy–ion experiments NA38 [6], NA50 [7] and NA60 [8] at the CERN-SPS, in PHENIX and STAR experiments [9] at RHIC as well as in recent ALICE experiments [10] at the CERN-LHC. Moreover, nowadays there are charmonium results in pA collisions at initial proton beam energy of 920 GeV from HERA-B experiment at the HERA proton ring of the DESY laboratory [11] and from E866 experiment at FNAL at beam energy of 800 GeV [12]. Various theoretical approaches have been proposed (see, e.g., [1–5, 13–28]) for the description of $J/\psi$ production in pA and AA interactions in the SPS, RHIC and LHC energy domains. The current theoretical and experimental status of the study of charmonium production in high-energy nuclear collisions is given in [33].

Due to almost negligible initial state interactions, the photon–nucleus reactions represent also an important and more transparent compared to proton–nucleus and heavy–ion collisions tool to investigate the charmonium in-medium properties, its interaction in cold nuclear matter. Several $J/\psi$ production experiments, using nuclear targets, have been performed at high photon energies, starting with 20 GeV (see Refs. [34–40]). The existing data on $J/\psi$ creation off only two nuclei (d, Be) below 20 GeV come from Cornell [41] using 9.3–11.8 GeV photons and from SLAC [42] from 13–21 GeV photons. No $J/\psi$ production events were observed in recent subthreshold JLab experiment [43], which used a carbon target and photons with energies below 6 GeV. So, it is not much is known presently in the region of the photon energies around the threshold energy of 8.2 GeV. All above calls for a new measurements in this region of photon energies. Various theoretical aspects of $J/\psi$ photoproduction on nuclei at high energies are discussed, e.g., in [44–51].

A particular interest was shown in recent years in the study of the charmonium production and suppression in proton–nucleus [52–54] and antiproton–nucleus [55–60] as well as in photon–nucleus [61, 62] reactions at energies close to the kinematic thresholds on free nucleons. This interest was triggered by the fact that these reactions are planned to be investigated in the near future in the CBM and PANDA experiments at the constructed FAIR facility in Germany [63] as well as at the upgraded up to 12 GeV CEBAF accelerator in the USA [64]. Since direct measurement of the fundamental $J/\psi$–nucleon inelastic cross section is not possible, analysis of data, collected in these experiments, will allow to perform a much improved determination of it because in low-energy collisions, contrary to the high-energy ones, the $J/\psi$ mesons are produced with low momenta relative to the nuclear medium at which their formation time (or color transparency) effects are expected to be insignificant and, therefore, the situation with the scattering of a full-sized charmonium (but not a compact $c\bar{c}$-pair) on an intranuclear nucleons with the full $J/\psi$ meson–nucleon cross section will be realized.

1) The threshold energy for $J/\psi$ photoproduction on a free nucleon being at rest is 8.2 GeV.
The primary goal of the present work is to extend the first collision model based on the nuclear spectral function [54] that has been adopted by us for the description of the A dependences of the absolute and relative (transparency ratio) $J/\psi$ meson yields as well as its excitation function in $pA$ collisions near threshold to $J/\psi$–producing electromagnetic processes. In this paper we present the estimates for the above observables from $\gamma A$ reactions in the near-threshold energy region obtained within this extended model. In view of the expected data from the JLab upgraded to 12 GeV, these estimates can be used as an important tool for determining the genuine $J/\psi$–nucleon absorption cross section as well as for understanding the properties of charmonium in nuclear medium and the role played by the various nucleus-related effects in the $J/\psi$ production near threshold.

2. Framework: a direct knock out processes

Since we are interested in the near-threshold incident photon energy region up to 11 GeV, we have taken into consideration the following elementary processes, which have the lowest free production threshold ($\approx 8.2$ GeV)\(^2\):

\[\gamma + p \rightarrow J/\psi + p,\]
\[\gamma + n \rightarrow J/\psi + n.\]

In line with [54], in the following calculations we will include the medium modification of the $J/\psi$ mesons, participating in the production processes (1), (2), by using, for reasons of simplicity, their average in-medium mass $<m_{J/\psi}^*>$ defined as:

\[<m_{J/\psi}^*> = \int d^3r \rho_N(r)m_{J/\psi}^*(r)/A,\]  

where $\rho_N(r)$ and $m_{J/\psi}^*(r)$ are the local nucleon density and $J/\psi$ effective mass inside the nucleus, respectively. Assuming that $m_{J/\psi}^*(r) = m_{J/\psi} + V_0\rho_N(r)/\rho_0$, we can readily rewrite equation (3) in the form

\[<m_{J/\psi}^*> = m_{J/\psi} + V_0\frac{<\rho_N>}{\rho_0}.\]

Here, $m_{J/\psi}$ is the $J/\psi$ free space mass, $<\rho_N>$ and $\rho_0 = 0.16$ fm\(^{-3}\) are the average and saturation nucleon densities, respectively. Our calculations show that, for example, for target nuclei $^{12}$C, $^{40}$Ca, $^{93}$Nb and $^{208}$Pb the ratio $<\rho_N>/\rho_0$ is approximately equal to 0.5, 0.6, 0.7 and 0.8, respectively. We will use the respective above values throughout the following study. In it in line with [54] for the $J/\psi$ mass shift at saturation density $V_0$ we will employ the five following options: i) $V_0 = 0$, ii) $V_0 = -25$ MeV, iii) $V_0 = -50$ MeV, iv) $V_0 = -100$ MeV, and v) $V_0 = -150$ MeV. It should be pointed out that according to the theory expectations [65–70] the $J/\psi$ mass shift at normal nuclear matter density is either very small or $\sim$-20 MeV due to a weak coupling of the $c$, $\bar{c}$ quarks to the nuclear medium. However, in reality it is unclear presently which shift is the correct one. Therefore, to extend the potential range of applicability of our model we will perform the calculations of the $J/\psi$ photoproduction cross sections off nuclei in the scenarios with possible charmonium mass shift.

\(^2\) We can neglect in the energy domain of our interest the following two-step $J/\psi$ production processes with $\chi_{c1}$, $\chi_{c2}$ and $\Psi'$ mesons in an intermediate states: $\gamma N \rightarrow \chi_{c1}N$, $\gamma N \rightarrow \chi_{c2}N$, $\gamma N \rightarrow \Psi'N$; $\chi_{c1} \rightarrow J/\psi\gamma$ (BR = 36%), $\chi_{c2} \rightarrow J/\psi\gamma$ (BR = 20%), $\Psi' \rightarrow J/\psi\pi\pi$ (BR = 49%) and $\Psi'N \rightarrow J/\psi N$ due to larger $\chi_{c1}$, $\chi_{c2}$ and $\Psi'$ production thresholds in $\gamma N$ collisions–10.1, 10.3 and 10.9 GeV, respectively.
that the virtual

\( \sigma_{V}(E_{\gamma}) = I_{V}[A] \left\langle \sigma_{\gamma N \rightarrow J/\psi N}(E_{\gamma}) \right\rangle_{A}, \)

where

\[ I_{V}[A] = 2\pi A \int_{0}^{R} \frac{\sqrt{R^{2} - r_{\perp}^{2}}}{-\sqrt{R^{2} - r_{\perp}^{2}}} dr_{\perp} \int dz \rho(\sqrt{r_{\perp}^{2} + z^{2}}) \exp \left[ \frac{\sqrt{R^{2} - r_{\perp}^{2}}}{A} \int_{z}^{\rho A}(x - z)\rho(\sqrt{r_{\perp}^{2} + x^{2})} dx \right], \]

\[ \left\langle \sigma_{\gamma N \rightarrow J/\psi N}(E_{\gamma}) \right\rangle_{A} = \int \int P_{A}(p_{t}, E)dp_{t}dE \sigma_{\gamma N \rightarrow J/\psi N}(\sqrt{s}, m_{J/\psi}^*), \]

and

\[ s = (E_{\gamma} + E_{t})^{2} - (p_{\gamma} + p_{t})^{2}, \]

\[ E_{t} = M_{A} - \sqrt{(-p_{t})^{2} + (M_{A} - m_{N} + E)^{2}}. \]

Here, \( \sigma_{\gamma N \rightarrow J/\psi N}(\sqrt{s}, m_{J/\psi}^*) \) is the "in-medium" total cross section for the production of \( J/\psi \) with reduced mass \( m_{J/\psi}^* \) in reactions (1) and (2) at the \( \gamma N \) center-of-mass energy \( \sqrt{s} \); \( \rho(r) \) and \( P_{A}(p_{t}, E) \) are the local nucleon density and the spectral function of target nucleus \( A \) normalized to unity\(^3\); \( p_{t} \) and \( E \) are the internal momentum and binding energy of the struck target nucleon just before the collision; \( A \) is the number of nucleons in the target nucleus, \( M_{A} \) and \( R \) are its mass and radius; \( m_{N} \) is the bare nucleon mass; \( p_{\gamma} \) and \( E_{\gamma} \) are the momentum and energy of the initial photon; \( \sigma_{\gamma N \rightarrow J/\psi N}^{eff}(z) \) is the \( J/\psi \)-nucleon effective absorption cross section, which will be defined below. The quantity \( I_{V}[A] \) in equation (6) represents the effective number of target nucleons participating in the primary \( \gamma N \rightarrow J/\psi N \) reactions. It should be noticed that the expression (7) for it is valid only at low photon energies at which the so-called coherence length \( l_{c} \) – the distance that the virtual \( \bar{c}c \) fluctuation of the incoming photon travels in the lab frame before scattering elastically on the nucleon–is much less than the nucleus size \( [59] \). Accounting for that the coherence length \( l_{c} = 2E_{\gamma}/m_{J/\psi}^{2} \) \([59]\), we get that at the photon energy \( E_{\gamma} = 11 \, \text{GeV} \), accessible at the JLab upgraded to 12 GeV, it is about of 0.5 fm. This is substantially less than the nucleus radius, which is to say that in the near-threshold \( J/\psi \) photoproduction on nuclei the \( \bar{c}c \)-pair is created essentially right at the location of the nucleon that it scatters from. After this scattering the compact \( \bar{c}c \) state evolves over some time (the formation time) or over some distance (the formation length, see also below) to form the final full-sized \( J/\psi \) meson.

Following [54], we assume that the "in-medium" cross section \( \sigma_{\gamma N \rightarrow J/\psi N}(\sqrt{s}, m_{J/\psi}^*) \) for \( J/\psi \) production in reactions (1) and (2) is equivalent to the vacuum cross section \( \sigma_{\gamma N \rightarrow J/\psi N}(\sqrt{s}, m_{J/\psi}) \) in which the free mass \( m_{J/\psi} \) is replaced by the average in-medium mass \( m_{J/\psi}^* \) as given by equation (5). For the free total cross section \( \sigma_{\gamma N \rightarrow J/\psi N}(\sqrt{s}, m_{J/\psi}) \) in the photon energy range \( E_{\gamma} \leq 22 \, \text{GeV} \) we have used the following parametrization, based on the near-threshold predictions of the two gluon exchange model [61]:

\[ \sigma_{\gamma N \rightarrow J/\psi N}(\sqrt{s}, m_{J/\psi}) = 11.1(1 - x)^{2} \, \text{[nb]}, \]

\[^{3}\text{In equation (6) it is assumed that the } J/\psi \text{ meson production cross sections in } \gamma p \text{ and } \gamma n \text{ interactions are the same [42].} \]

\[^{4}\text{The specific information about these quantities, used in our subsequent calculations, is given in [71, 72].}\]
where

\[ x = \frac{(s_{\text{thr}} - m_{N}^{2})}{(s - m_{N}^{2})}, \quad s_{\text{thr}} = (m_{J/\psi} + m_{N})^{2}, \quad s = (E_{\gamma} + m_{N})^{2} - p_{\gamma}^{2}. \] (12)

The comparison of the results of calculations by (11) (solid line) with the scarce existing data from "Cornell 75" [41] (full dot), "SLAC 75" [42] (full triangles) and "SLAC 76 unpublished" [73] (open triangles), collected together in [64], is shown in figure 1. It can be seen that the parametrization (11) fits well the existing set of data for the \( \gamma N \rightarrow J/\psi N \) reaction in the considered range of photon energies.

Figure 1: (color online) Total cross section for the reaction \( \gamma N \rightarrow J/\psi N \) as a function of photon energy. The arrow indicates its threshold on a free nucleon. For notation see the text.

Following [54, 56, 59, 74], we express the charmonium–nucleon effective cross section \( \sigma_{\text{eff}}^{J/\psi N}(z) \), entering into the equation (7) and taking into account the time dependence of the \( J/\psi \) formation, in terms of a \( J/\psi \) meson formation length \( l_{J/\psi} \):

\[
\sigma_{\text{eff}}^{J/\psi N}(z) = \sigma_{J/\psi N} \left\{ \theta(l_{J/\psi} - z) \left[ \frac{z}{l_{J/\psi}} + \frac{n^{2} < k_{t}^{2} >}{m_{J/\psi}^{2}} \left( 1 - \frac{z}{l_{J/\psi}} \right) \right] + \theta(z - l_{J/\psi}) \right\}. \] (13)

Here, \( \sigma_{J/\psi N} \) is the genuine free-space \( J/\psi \)–nucleon absorption cross section; \( n \) is the number of valence quarks of the hadron (\( n = 2 \) in our case), while \( < k_{t}^{2} >^{1/2} \) is the average transverse momentum of the quark in the hadron (taken to be \( < k_{t}^{2} >^{1/2} = 0.35 \) GeV/c); \( z \) is the distance from the production point of the \( c\bar{c} \)-pair which evolves over the formation length \( l_{J/\psi} \) into the final \( J/\psi \) meson and \( \theta(x) \) is the standard step function. For the \( J/\psi \) meson formation length \( l_{J/\psi} \) we adopt the conventional formula with an energy denominator [54, 56, 59, 74]:

\[
l_{J/\psi} \approx \frac{2p_{J/\psi}^{\text{lab}}}{m_{J/\psi}^{2} - m_{J/\psi}^{2}} \approx 0.1 \text{ fm} \frac{p_{J/\psi}^{\text{lab}}}{(\text{GeV}/c)}, \] (14)

where \( p_{J/\psi}^{\text{lab}} \) is the charmonium momentum in the target nucleus rest frame. Taking into consideration that the average momentum between the maximum and minimum allowable momenta in the process

\[ \approx (s_{\text{thr}} - m_{N}^{2})/2m_{N} \] is the energy at kinematic threshold.

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5) It is easily seen that also \( x = E_{\gamma}^{\text{thr}}/E_{\gamma} \), where \( E_{\gamma}^{\text{thr}} = (s_{\text{thr}} - m_{N}^{2})/2m_{N} \) is the energy at kinematic threshold.
\( \gamma N \rightarrow J/\psi N \) proceeding on a free target nucleon being at rest at initial photon energy of 11 GeV is \( p_{J/\psi}^{\text{lab}} \approx 7.7 \text{ GeV/c} \), one can get that \( l_{J/\psi} \approx 0.8 \text{ fm} \) for this momentum. We will use this value for the quantity \( l_{J/\psi} \) throughout our calculations for a collection of \( A \) target nucleons subject to Fermi motion in the near-threshold energy domain. Ignoring the struck target nucleon binding and Fermi motion and outgoing \( J/\psi \) in-medium modifications, from (6) we get the following simple expression for the total cross section \( \sigma_{\gamma A \rightarrow J/\psi X}(E_\gamma) \):

\[
\sigma_{\gamma A \rightarrow J/\psi X}^{(\text{prim})}(E_\gamma) = I_V[A] \sigma_{\gamma N \rightarrow J/\psi N}(\sqrt{s}, m_{J/\psi}),
\]

(15)

where the elementary cross section \( \sigma_{\gamma N \rightarrow J/\psi N}(\sqrt{s}, m_{J/\psi}) \) is given by (11). It is valid only in a photon energy range above threshold (see figures 2, 5 and 6, given below) and allows one to easily estimate here this cross section.

The absorption cross section \( \sigma_{J/\psi N} \) can be extracted, in particular, from a comparison of the calculations with the measured transparency ratio of the \( J/\psi \) meson, normalized, for example, to carbon:

\[
T_A = \frac{12}{A} \frac{\sigma_{\gamma A \rightarrow J/\psi X}(E_\gamma)}{\sigma_{\gamma C \rightarrow J/\psi X}(E_\gamma)}.
\]

(16)

Here, \( \sigma_{\gamma A \rightarrow J/\psi X}(E_\gamma) \) and \( \sigma_{\gamma C \rightarrow J/\psi X}(E_\gamma) \) are inclusive total cross sections for \( J/\psi \) production in \( \gamma A \) and \( \gamma C \) collisions at incident photon energy \( E_\gamma \), respectively. If the primary photon–induced reaction channels (1), (2) dominate in the \( J/\psi \) production in \( \gamma A \) reactions close to threshold \( \delta \), then, according to (6) and (7), we have:

\[
T_A = \frac{12}{A} \frac{\sigma_{\gamma A \rightarrow J/\psi X}^{(\text{prim})}(E_\gamma)}{\sigma_{\gamma C \rightarrow J/\psi X}^{(\text{prim})}(E_\gamma)} = \frac{12}{A} \frac{I_V[A]}{I_V[C]} \left\langle \frac{\sigma_{\gamma N \rightarrow J/\psi N}(E_\gamma)}{A} \right\rangle_A \left\langle \frac{\sigma_{\gamma N \rightarrow J/\psi N}(E_\gamma)}{C} \right\rangle_C.
\]

(17)

Ignoring the difference between the cross sections \( \left\langle \frac{\sigma_{\gamma N \rightarrow J/\psi N}(E_\gamma)}{A} \right\rangle_A \) and \( \left\langle \frac{\sigma_{\gamma N \rightarrow J/\psi N}(E_\gamma)}{C} \right\rangle_C \), from (17) we approximately obtain:

\[
T_A \approx \frac{12}{A} \frac{I_V[A]}{I_V[C]}.
\]

(18)

As is easy to see from (13), when \( J/\psi \) formation length \( l_{J/\psi} \rightarrow 0 \) then the exponent in equation (7) can be put in the following in an easy-to-use in analytical integration form:

\[
A \sigma_{J/\psi N} \int_z \rho(\sqrt{r_\perp^2 + x^2})dx.
\]

(19)

In this case the integral (7) for the quantity \( I_V[A] \) can be transformed to a simpler expression:

\[
I_V[A] = \frac{\pi}{\sigma_{J/\psi N}} \int_0^{R_\perp^2} \left( 1 - e^{-A \sigma_{J/\psi N} \int \frac{\rho(\sqrt{r_\perp^2 + x^2})dx}{\sqrt{R_\perp^2 - r_\perp^2}}} \right),
\]

(20)

\( ^6 \)One may expect that this is so due to the following. The main inelastic channel in \( \gamma N \) collisions at beam energies of interest is the multiplicity production of pions with comparatively low energies at which the secondary \( \pi N \rightarrow J/\psi X \) processes are energetically suppressed.

\( ^7 \)This difference is small (within several percent) both at above threshold incident energies and at energies just below the threshold, as our calculations by (17) and (18) for the nucleus with a diffuse boundary showed. However, it becomes substantial at far subthreshold beam energies as our calculations also demonstrated (compare, for example, short-dashed and solid lines in figure 4 given below). It is easily seen that, according to equations (15), (17), the expression (18) describes the transparency ratio \( T_A \) also in the case when primary \( \gamma N \rightarrow J/\psi N \) processes proceed on a free target nucleon being at rest without \( J/\psi \) in-medium modifications.
which in the cases of Gaussian nuclear density \((\rho(r) = (b/\pi)^{3/2} \exp(-br^2))\) and a uniform nucleon density for a nucleus of a radius \(R = r_0A^{1/3}\) with a sharp boundary is reduced to even more simple forms:

\[
I_V[A] = \frac{A}{x_G} \int_0^1 \frac{dt}{t} \left(1 - e^{-x_Gt}\right), \quad x_G = A\sigma_{J/\psi N}b/\pi \tag{21}
\]

and

\[
I_V[A] = \frac{3A}{2a_1} \left\{1 - \frac{2}{a_1^2} [1 - (1 + a_1)e^{-a_1}]\right\}, \quad a_1 = 3A\sigma_{J/\psi N}/2\pi R^2, \tag{22}
\]

respectively. The simple formulas (15), (21), (22) and (18), (21), (22) allow one to easily estimate both the total cross section \(\sigma_{\gamma A \rightarrow J/\psi X}(E_\gamma)\) at above threshold energies and the transparency ratio \(T_A\) here as well as at initial energies not far below the threshold (see figures 3 and 4 given below).

Let us discuss now the results of our calculations in the framework of the approach outlined above.

3. Results and discussion

Figure 2 shows the A–dependence of the total \(J/\psi\) production cross section from the primary \(\gamma N \rightarrow J/\psi N\) reaction channels in \(\gamma A\) \((A = ^{12}\text{C}, ^{27}\text{Al}, ^{40}\text{Ca}, ^{93}\text{Nb}, ^{208}\text{Pb}, \text{and} ^{238}\text{U})\) collisions calculated for incident photon energy of \(E_\gamma = 11\) GeV on the basis of equations (6) and (15) for the same values of the genuine charmonium–nucleon absorption cross section \(\sigma_{J/\psi N}\), as those used in [54] and indicated in the inset, and for no \(J/\psi\) mass shift. As in [54], the calculations with only \(l_{J/\psi} = 0 \text{ in equation (7)}\) are given in the figure for \(\sigma_{J/\psi N} = 7\) mb and \(\sigma_{J/\psi N} = 14\) mb, for the case of \(\sigma_{J/\psi N} = 3.5\) mb the ones are presented here already for two options, namely: i) \(l_{J/\psi} = 0\) and ii) \(l_{J/\psi} = 0.8\) fm. One can see that, as in the case of \(pA\) reactions [54], the results are practically insensitive to the \(J/\psi\) formation time effects, but they depend strongly for heavy target nuclei on the charmonium–nucleon absorption cross section. We see yet that for the incoming photon energy of 11 GeV the value of the absolute \(J/\psi\) meson yield is of the order of 20–140 nb for targets heavier than the Al target in employed four scenarios for the cross section \(\sigma_{J/\psi N}\). This value is large enough to be measured in the future CEBAF experiments. Therefore, one can conclude that, as before in [54], the observation of the A dependence, like that just considered, offers the possibility to determine the genuine \(J/\psi N\) absorption cross section. The comparison of the results of calculations of the total cross section of \(J/\psi\) photoproduction from primary \(\gamma N \rightarrow J/\psi N\) reaction channels for \(\sigma_{J/\psi N} = 14\) mb with and without accounting for target nucleon binding and Fermi motion indicates that the neglecting of the nuclear effects on the struck target nucleon leads to an enhancement of the \(J/\psi\) yield by about a factor of 1.2. According to equations (6) and (15), this is due to the fact that the averaged over the struck target nucleon binding and Fermi motion elementary cross section \(\sigma_{\gamma \rightarrow J/\psi X}(E_\gamma)\) at \(E_\gamma = 11\) GeV is reduced by the same factor compared to free one (11) calculated at above energy.

In figure 3 our predictions for the transparency ratio \(T_A\), defined by equations (17), (18) and calculated using the results presented in figure 2, as a function of the nuclear mass number A for initial photon energy of 11 GeV are given. It can be seen that, as in the preceding case as well as in the case of near-threshold charmonium production in \(pA\) collisions considered in [54], there are no differences between the results obtained by adopting different \(J/\psi\) formation lengths under consideration. On the other hand, we may observe in this figure the experimentally separated differences \((\sim 15–20\%)\) between all calculations corresponding to different options for the \(J/\psi N\) absorption cross section only for targets heavier than the Nb target, where they are less than \(\sim 10\%\).

The above means that also this observable can be used for determining the cross section \(\sigma_{J/\psi N}\) from the future CEBAF photoproduction experiments using the heavy targets like Pb. Looking at this
Figure 2: (color online) $A$–dependence of the total cross section of $J/\psi$ production by 11 GeV photons in the full phase space from primary $\gamma N \rightarrow J/\psi N$ reactions proceeding on an off-shell target nucleons and on a free ones being at rest in the scenario without $J/\psi$ mass shift for different values of the $J/\psi N$ absorption cross section and $J/\psi$ formation length indicated in the inset. The lines are to guide the eyes.

Figure 3: (color online) Transparency ratio $T_A$ for $J/\psi$ mesons from primary $\gamma N \rightarrow J/\psi N$ reactions proceeding on an off-shell target nucleons and on a free ones being at rest as a function of the nuclear mass number $A$ in the scenario without their mass shift as well as for their different absorption cross sections and formation lengths indicated in the inset. The lines are to guide the eyes.

In the figure, one can see yet that the difference between calculations for $\sigma_{J/\psi N} = 14$ mb with and without accounting for target nucleon binding and Fermi motion (between two lower curves) is only of the
order of 4%. This indicates clearly that indeed the simple formula (18) is well suited for calculation
the transparency ratio $T_A$ at above threshold energies. It is also nicely seen that this quantity is
practically constant at the level of about 0.96 in the case of calculations without $J/\psi$ absorption
in nuclear medium (upper curve in figure 3). In this case, it is determined, in line with equations
(7) and (17), by the ratio of the averaged cross sections $<\sigma_{\gamma N \rightarrow J/\psi N}(E_{\gamma} = 11 \text{ GeV})>_A$
and $<\sigma_{\gamma N \rightarrow J/\psi N}(E_{\gamma} = 11 \text{ GeV})>_C$, which is approximately equal to 0.96 as our calculations showed.

Figure 4: (color online) Transparency ratio $T_A$ for $J/\psi$ mesons from primary $\gamma N \rightarrow J/\psi N$ reactions
proceeding on an off-shell target nucleons as a function of the incident photon energy for combination
Pb/C. The curves are calculations by formula (17) for the nucleus with a diffuse boundary for
$\sigma_{J/\psi N} = 3.5 \text{ mb}$ and $l_{J/\psi} = 0$ with an in-medium $J/\psi$ mass shift depicted in the inset. The short-
dashed straight line is the calculation for the nucleus with a diffuse boundary by the expression
(18) also for $\sigma_{J/\psi N} = 3.5 \text{ mb}$ and $l_{J/\psi} = 0$. The arrow indicates the threshold energy for $J/\psi$
photoproduction on a free nucleon.

Figure 4 presents transparency ratio $T_A$ for $J/\psi$ mesons from primary $\gamma N \rightarrow J/\psi N$ reactions
as a function of the initial photon energy for Pb/C combination. It was calculated on the basis of the simple formula (18) for the same
values of $\sigma_{J/\psi N}$ and $l_{J/\psi}$ are given here as well. It can be seen that the difference between the
various options is very small at above threshold incident photon energies $\sim 10$–$11 \text{ GeV}$, while the highest sensitivity to the $J/\psi$ in-medium mass shift is found, as is expected, in the far subthreshold
region ($E_{\gamma} \sim 5$–$7 \text{ GeV}$). Here, the transparency ratio is enhanced by a factor of about 1.05 when going from $J/\psi$ mass shift at normal nuclear matter density $V_0 = 0 \text{ MeV}$ to $V_0 = -25 \text{ MeV}$ as well as by about the same factor of 1.1 when going from $V_0 = -25 \text{ MeV}$ to $V_0 = -50 \text{ MeV}$ as
when going from $V_0 = -50 \text{ MeV}$ to $V_0 = -100 \text{ MeV}$ and again by about the same factor of 1.1
when going from $V_0 = -100 \text{ MeV}$ to $V_0 = -150 \text{ MeV}$. On the other hand, it is enhanced here by a
factor of about 1.2 when going from $V_0 = 0 \text{ MeV}$ to $V_0 = -50 \text{ MeV}$ as well as by about a factor of
1.3 when going from $V_0 = -50 \text{ MeV}$ to $V_0 = -150 \text{ MeV}$. It is apparent that the latter case opens
an opportunity to distinguish experimentally at least between possible zero, relatively weak ($\sim 50$
MeV) and strong ($\sim 150 \text{ MeV}$) charmonium mass shifts in cold nuclear matter. But smaller mass
Figure 5: (color online) Excitation function for production of $J/\psi$ mesons off $^{12}$C from primary $\gamma N \rightarrow J/\psi N$ reactions proceeding on an off-shell target nucleons and on a free ones being at rest. The curves are calculations for $\sigma_{J/\psi N} = 3.5$ mb and $l_{J/\psi} = 0$ with an in-medium $J/\psi$ mass shift depicted in the inset. The arrow indicates the threshold energy for $J/\psi$ photoproduction on a free nucleon.

Figure 6: (color online) The same as in figure 5, but for the $^{208}$Pb target nucleus.

shifts, closer to the theory expectations, will probably not accessible by measuring the transparency ratio at subthreshold photon energies. By looking at this figure, one can also see that the simple expression (18) describes the considered transparency ratio quite well at incident photon energies of 7–11 GeV (compare short-dashed and solid curves), while it fails to do that at lower beam energies.

Now, we consider the excitation functions for production of $J/\psi$ mesons off $^{12}$C and $^{208}$Pb target
Figure 7: (color online) Ratio between the $J/\psi$ production cross sections on $^{12}$C with the $J/\psi$ mass shift, shown in figure 5, and the cross section without this shift, calculated for an off-shell target nucleons, as a function of photon energy. The arrow indicates the threshold for the reaction $\gamma N \rightarrow J/\psi N$ occurring on a free nucleon.

Figure 8: (color online) Ratio between the $J/\psi$ production cross sections on $^{208}$Pb with the $J/\psi$ mass shift, shown in figure 6, and the cross section without this shift, calculated for an off-shell target nucleons, as a function of photon energy. The arrow indicates the threshold for the reaction $\gamma N \rightarrow J/\psi N$ occurring on a free nucleon.

nuclei. As in [54], they were calculated on the basis of equation (6) for $\sigma_{J/\psi N} = 3.5$ mb, $l_{J/\psi} = 0$ and for five adopted scenarios for the $J/\psi$ in-medium mass shift as well as in line with formula (15) for free target nucleon being at rest with the same values of $\sigma_{J/\psi N}$ and $l_{J/\psi}$, and are given in figures
5 and 6. It is seen that the difference between calculations with and without accounting for the target nucleon Fermi motion (between short-dashed and solid curves) is small at above threshold photon energies $\sim 9–11$ GeV, while at lower incident energies its influence on $J/\psi$ yield is quite essential. At energies of $\sim 9–11$ GeV the difference between the various scenarios for in-medium $J/\psi$ mass shift is also small. But in the far subthreshold region ($E_\gamma \sim 5–7$ GeV) there are well separated predictions for considered scenarios for the $J/\psi$ in-medium mass shift. The values of the total charmonium production cross sections in this region are very small (in the range of 0.1–1000 pb), but one might expect to measure their in the future CEBAF experiments as well. Therefore, these measurements might help to get definite information about this shift.

To get a better impression of the size of the effect of $J/\psi$ meson in-medium mass shift on its yield in $\gamma C \rightarrow J/\psi X$ and $\gamma Pb \rightarrow J/\psi X$ reactions, in figures 7 and 8 we show the ratios between the cross sections with mass shift and the cross sections with $V_0 = 0$ MeV, calculated using the results presented in figures 5 and 6, respectively. It can be seen that the possibility of studying the $J/\psi$ mass shift from the excitation function measurements is feasible only in the range of mass shifts of -50 MeV and more at far subthreshold beam energies ($E_\gamma \sim 5–7$ GeV), while smaller mass shifts will be not accessible by these measurements. This is consistent with our previous findings of figure 4 and of [54].

Taking into account the above considerations, we come to the conclusion that such observables as the absolute and relative (transparency ratio) $J/\psi$ meson yields from $\gamma A$ interactions can be useful at photon beam energies above the kinematic threshold to help determine the genuine $J/\psi N$ absorption cross section. Having this cross section fixed, the excitation function measurements at incident photon energies below the production threshold on the free nucleon, where the effect of the charmonium mass shift in cold nuclear matter is dominant, will allow to shed light on the possible mass shifts in the range of -50 MeV and more.

4. Conclusions

In this paper we have calculated the A dependence of the absolute and relative (transparency ratio) cross sections for $J/\psi$ production from $\gamma A$ collisions at 11 GeV beam energy by considering incoherent direct photon–nucleon charmonium production processes in the framework of a nuclear spectral function approach, which accounts for the struck target nucleon momentum and removal energy distribution, elementary cross section for photon–nucleon reaction channel close to threshold as well as different scenarios for the genuine $J/\psi N$ absorption cross section and its formation length. Also we have calculated the absolute and relative excitation functions for $J/\psi$ production off $^{12}$C and $^{208}$Pb target nuclei at near-threshold incident photon energies of 5–11 GeV. It was found that the absolute and relative $J/\psi$ yields at incident energies of 9–11 GeV, on the one hand, is practically not influenced by formation length and mass shift effects and, on the other hand, it is appreciably sensitive to the charmonium–nucleon absorption cross section. This gives a nice opportunity to determine it experimentally studying the above observables in this energy domain. It was also shown that the absolute and relative excitation functions for $J/\psi$ production off nuclei is well sensitive to the possible $J/\psi$ in-medium mass shifts in the range of -50 MeV and more at subthreshold beam energies, and this offers the possibility to investigate such shifts via $J/\psi$ production on light and heavy target nuclei at these energies.

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