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How can the photon-like heavy quarkonium $V \to Q\bar{Q}$ transition falsify our predictions ?

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The diffractive electroproduction of heavy quarkonia (V) is an effective tool to study the structure of $V \to Q\bar{Q}$ transition. The most of existing studies in the literature are based on the unjustified assumption of a similar structure of both $\gamma \to Q\bar{Q}$ and $V \to Q\bar{Q}$ vertices, typically performed in the light-front frame. Such the photon-like $V \to Q\bar{Q}$ vertex, besides the S-wave component, also contains an extra D-wave admixture in the $Q\bar{Q}$ rest frame. However, the relative weight of this contribution cannot be justified by any reasonable nonrelativistic $Q - \bar{Q}$ potential model. Consequently, the recent model predictions for heavy quarkonium photoproduction cross sections are thus contaminated by these D-wave effects, which may lead to serious problems with a correct interpretation of the experimental data. In this work, we investigate and discuss the relative role of the D-wave contribution by comparison of our predictions based on the photon-like structure with results within a simple S-wave-only form of the quarkonium vertex. Calculations performed in the color dipole formalism are tested by available data. We have found that the production of radially excited heavy quarkonium states is more effective for the study of the $V \to Q\bar{Q}$ vertex structure due to a stronger sensitivity of the undesirable D-wave contribution to a nodal structure of quarkonium wave functions.

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1. Introduction

The elastic (coherent) photo- and electroproduction of heavy quarkonia ($J/\psi(1S)$, $\psi'(2S)$, $\Upsilon(1S)$, $\Upsilon'(2S)$,...) is one of the fundamental tools to study various aspects of Quantum Chromodynamics (QCD), such as gluon distribution, saturation scale phenomena, low-x physics dynamics, etc. Heavy quarkonium production off nuclei plays an important role in the investigation of properties of both a cold nuclear matter and a dense and hot medium created after heavy-ion collisions. In the latter case, it can be treated as a thermometer for a hot medium due to the flavor dependence of quarkonium binding energies and the corresponding dissociation temperatures.

The large mass of heavy quarks in quarkonium production allows minimizing to a certain extent a contribution from the nonperturbative region of QCD in calculations of production amplitudes. In the diffractive photoproduction process, the light-front (LF) wave function of the photon is well described without significant uncertainties. However, the quarkonium LF wave functions are rather ambiguous. Nevertheless, they are well defined in the $Q\bar{Q}$ rest frame relying on the Schrödinger equation with various models for $Q-\bar{Q}$ interaction potentials. This requires to perform the Lorentz boost subsequently to the LF frame as described in [1].

The most of studies of quarkonium electroproduction off protons and nuclei is based on an unjustified assumption of a similar structure of both $\gamma^* \to Q\bar{Q}$ and $V \to Q\bar{Q}$ transitions. This leads to an undesirable D-wave admixture in the $Q\bar{Q}$ rest frame which is not proven by any nonrelativistic $Q-\bar{Q}$ potential model. Although a small relative weight of such D-wave component is expected in $J/\psi(1S)$ photoproduction, D-wave effects can lead to a dramatic impact on magnitudes of cross sections in production of radially excited states, such as $\psi'(2S)$, $\psi''(3S)$, etc.

In this report, we analyze the relative contribution of undesirable D-wave admixture treating two scenarios. The first denoted as the scenario I, corresponds to the photon-like structure of the quarkonium vertex directly in the LF frame. The second scenario II is based on the "S-wave-only" $V \to Q\bar{Q}$ transition in the $Q\bar{Q}$ rest frame as studied in Refs. [2, 3]. Consequently, the latter scenario requires to perform the corresponding Lorentz boost also for the spin-dependent components of quarkonium wave functions known as the Melosh spin rotation [4].

2. Scenarios for $V \to Q\bar{Q}$ transition

Here we restrict to photoproduction (photon virtuality $Q^2 \to 0$) of heavy quarkonia off protons and nuclei with the description within the LF color dipole approach. The D-wave effects are studied treating two different scenarios:

Scenario I corresponds to the photon-like $V \to Q\bar{Q}$ structure with the following photon-like form of the T-polarized operator in the spinor space,

$$\hat{O}_T \quad = \quad m_Q\vec{\sigma}\cdot\vec{e}_V + i(1-2z)(\vec{\sigma}\cdot\vec{n})(\vec{e}_V\cdot\vec{\nabla}_r) + (\vec{n}\times\vec{e}_V)\cdot\vec{\nabla}_r\,, \tag{1}$$

where m_Q is the quark mass, $\vec{\sigma}$ is the vector of Pauli matrices, $\vec{e}_V$ is the quarkonium polarisation vector, $\vec{n} = \vec{p}_V/|\vec{p}_V|$ is the unit vector directed along with the quarkonium momentum and $z = p^+_Q/p^+_V$ is the boost-invariant fraction of the quarkonium momentum carried by a heavy quark.

Taking into account the structure (1) the imaginary part of the nucleon photoproduction amplitude reads,

$$\begin{aligned} \mathrm{Im}\,\mathcal{A}_N^I(x) &= N_1 \int d^2r \int_0^1 dz\, \sigma_{Q\bar{Q}}(x,r) \left[\Sigma^{(1)}(r,z) + \Sigma^{(2)}(r,z)\right], \\ \Sigma^{(1)}(r,z) &= m_Q^2 K_0(m_Q r) \int_0^\infty dp_T\, p_T J_0(p_T r) \Psi_V(z,p_T), \\ \Sigma^{(2)}(r,z) &= m_Q[z^2 + (1-z)^2] K_1(m_Q r) \int_0^\infty dp_T\, p_T^2 J_1(p_T r) \Psi_V(z,p_T)\,, \end{aligned} \tag{2}$$

where $N_1 = Z_Q\sqrt{2N_c^2\,\alpha_{em}}/2\pi$, the factor $N_c = 3$ represents the number of colors in QCD, Z_Q is the charge isospin factor for a heavy quarkonium, $J_{0,1}$ and $K_{0,1}$ are the Bessel functions of the first kind and the modified Bessel functions of the second kind, respectively, and $\Psi_V(z,p_T)$ is the LF wave function for heavy quarkonium. The dipole cross section $\sigma_{Q\bar{Q}}(x,r)$ in (2) describes the interaction of $Q\bar{Q}$ pair of a transverse separation r with a nucleon.

Specifically, considering a harmonic oscillator (HO) form of the $Q-\bar{Q}$ potential in the $Q\bar{Q}$ rest frame, one can obtain explicitly the well known *boosted Gaussian wave function* [5] performing the boost to the LF frame. Note, that HO potential suffers from the absence of the hard Coulomb interaction and thus cannot be applied properly for determination of quarkonia wave functions, especially for radially excited states.

Note that the onset of D-wave component in meson rest frame follows from the second derivative term in Eq. (1). Then the quarkonium wave function contains besides the S-wave also a D-wave contribution. However, the relative weight of such D-wave component is not justified and cannot be obtained within any model for the $Q-\bar{Q}$ interaction potential.

Scenario II is related to the "S-wave-only" $V \to Q\bar{Q}$ transition with the following simple structure of the T-polarized operator in the spinor space,

$$\hat{O}_T = \vec{\sigma} \cdot \vec{e}_V\,. \tag{3}$$

Here, in comparison with the scenario I, since the spin-orbital part of quarkonium wave functions is treated in the $Q\bar{Q}$ rest frame, one should perform additionally the corresponding Lorentz boost (the Melosh spin transformation [4, 6]) of two-dimensional heavy quark spinors to the LF frame.

Considering the structure for $\hat{O}_T$ given by Eq. (3) and including spin rotation effects, the imaginary part of nucleon photoproduction amplitude has the following form,

$$\begin{aligned} \mathrm{Im}\,\mathcal{A}_N^{II}(x) &= \frac{N_2}{2} \int d^2r \int_0^1 dz\, \sigma_{Q\bar{Q}}(x,r) \left[\Sigma_M^{(1)}(r,z) + \Sigma_M^{(2)}(r,z)\right], \\ \Sigma_M^{(1)}(r,z) &= K_0(m_Q r) \int_0^\infty dp_T\, p_T J_0(p_T r) \Psi_V(z,p_T) \frac{2m_Q^2(m_L + m_T) + m_L p_T^2}{m_T(m_L + mT)}, \\ \Sigma_M^{(2)}(r,z) &= K_1(m_Q r) \int_0^\infty dp_T\, p_T^2 J_1(p_T r) \Psi_V(z,p_T) \frac{m_Q^2(m_L + 2m_T) - m_T m_L^2}{m_Q m_T(m_L + mT)}\,, \end{aligned} \tag{4}$$

where $N_2 = Z_Q\sqrt{2N_c\,\alpha_{em}}/2\pi$, $m_T = \sqrt{m_Q^2 + p_T^2}$ and $m_L = 2\,m_Q\,\sqrt{z(1-z)}$.

In our calculations of photoproduction cross sections we have included also a small correction for the real part of amplitudes $\mathcal{A}_N^I$ and $\mathcal{A}_N^{II}$ via the following expression,

$$\left|\mathcal{A}_N(x)\right|^2 = \left|\mathrm{Im}\mathcal{A}_N(x)\right|^2 \left[1 + \left(\frac{\pi}{2}\frac{\partial\ln(\mathrm{Im}\mathcal{A}_N(x))}{\partial\ln 1/x}\right)^2\right]. \tag{5}$$

Then the total cross section for the exclusive quarkonium photoproduction on a proton target reads,

$$\sigma^{\gamma p \to V p}(x) = \frac{1}{16\pi B}\left|\mathcal{A}_N(x)\right|^2, \tag{6}$$

where we took $B = 4.73$ GeV^{-2} for the slope parameter.

Besides the photoproduction of quarkonia off protons, we also analyze their production in heavy-ion ultra-peripheral collisions (UPC) where the photo-nuclear reaction can be induced by the photon from one of the colliding nuclei. The corresponding cross section for coherent quarkonium production off nuclei reads,

$$\frac{d\sigma^{AA}}{dy} = \int d^2\tau \int d^2b\, n(k, \vec{b} - \vec{\tau})\frac{d^2\sigma^{\gamma A}(x, b, y)}{d^2b} \quad + \quad \left\{y \to -y\right\}, \tag{7}$$

where $n(k, \vec{b} - \vec{\tau})$ is the photon flux with the photon energy $k = m_V\sqrt{s}\, e^y/2m_N$ [3], where m_V and m_N is the quarkonium and nucleon mass, $x = m_V^2/s$, $s = m_N^2 + 2km_N \approx W^2$ and the coherent nuclear cross section is given as,

$$\frac{d^2\sigma^{\gamma A \to V A}(x, b)}{d^2b} \quad = \quad \left|\mathcal{A}_A(x, b)\right|^2 . \tag{8}$$

Here the nuclear amplitude $\mathcal{A}_A(x, b)$ related to scenarios I and II is obtained from Eqs. (2) and (4) performing the following substitution in terms of the nuclear thickness function $T_A(b)$,

$$\sigma_{Q\bar{Q}}(x, r) \Rightarrow 1 - \exp\left[-\frac{1}{2}\sigma_{Q\bar{Q}}(x, r)T_A(b)\right] , \tag{9}$$

corresponding to the eikonal form for the higher twist quark shadowing assuming asymptotic large photon energies related to long-lived $Q\bar{Q}$ photon fluctuations. However, in our analysis, we have included corrections for the finite photon energies, as well as the leading twist gluon shadowing which have been calculated using a rigorous Green function formalism as presented in Ref. [3].

3. Numerical results

In our model predictions, we have adopted quarkonium wave functions generated by the Buchmuller-Tye $Q - \bar{Q}$ interaction potential [7], as well as the GBW phenomenological model [8] for the dipole cross section.

As the first test, our model calculations within both scenarios I and II are compared in Fig. 1 with available data on $J/\psi(1S)$ photoproduction as function of c.m. energy W (left panel). Here one can see a reasonable agreement of our predictions with data. Simultaneously, the relative undesirable onset of D-wave contribution demonstrated as a difference between the solid and dashed line causes only a small $\sim 5 \div 10\%$ enhancement of charmonium photoproduction cross section that cannot be identified by data within the given error bars.

However, there is a chance for identification of a negative role of D-wave effects in the production of radially excited charmonium states or treating the $\psi'(2S)$-to-$J/\psi(1S)$ ratio of photoproduction cross section as is demonstrated in the right panel of Fig. 1. Now the D-wave contribution causes $\sim 25\%$ enhancement of the $2S$-to-$1S$ ratio. Available data are not sufficiently precise to make

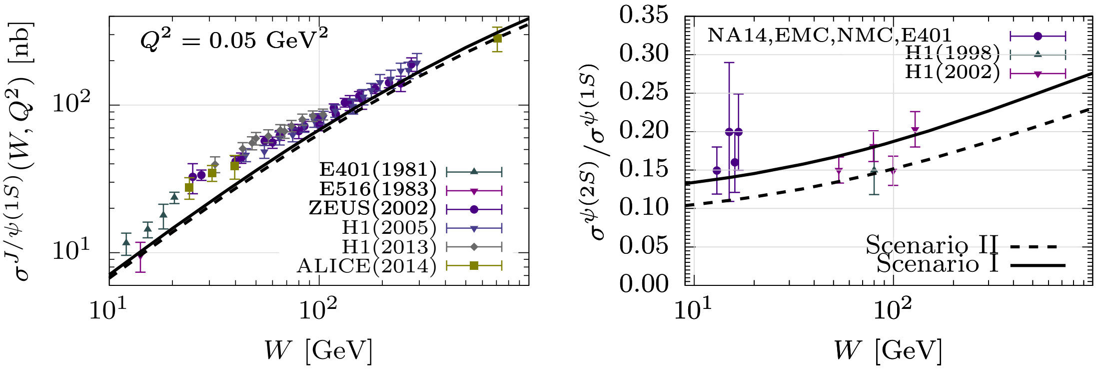

Figure 1: Comparison of the both scenarios I and II in exclusive charmonium photoproduction off protons: (Left panel) Predictions for the cross section of the process $\gamma p \to J/\psi p$ as functions of $\gamma - p$ collision energy W at fixed $Q^2 = 0.05$ GeV^2. (Right panel) The same as the left panel but for the $\psi'(2S)$-to-$J/\psi(1S)$ cross section ratio. For the experimental data, see references in [1].

a final conclusion about a preference of scenario II without D-wave admixture. More precise data from future electron-ion colliders (EICs) can be effective for the study of the quarkonium vertex.

Note that the study of $2S$-to-$1S$ ratio of cross sections for quarkonium photoproduction off protons and nuclei allows reducing the main theoretical uncertainties inherent from the LF color dipole formalism and related to the shape of quarkonium wave functions generated by various $Q-\bar{Q}$ interaction potentials, as well as to different models for the dipole cross section.

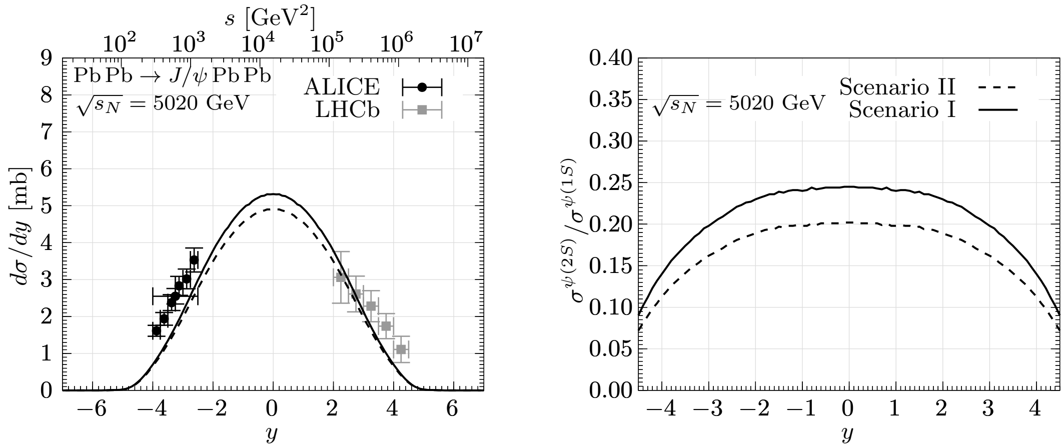

Figure 2: Comparison of the both scenarios I and II in charmonium production in UPC at LHC: (Left panel) Predictions for the cross section of the coherent process $Pb\,Pb \to J/\psi\;Pb\,Pb$ as function of rapidity at fixed collision energy $\sqrt{s_N} = 5020$ GeV. (Right panel) The same as the left panel but for the $\psi'(2S)$-to-$J/\psi(1S)$ cross section ratio. For the experimental data, see references in [3].

The undesirable D-wave admixture in charmonium wave functions can also be seen in heavy-ion UPC as is demonstrated in the left panel of in Fig. 2. It causes ~ 10% enhancement of $d\sigma/dy$ visible mostly at midrapidity ($y = 0$) and thus can be hardly identified by recent forthcoming LHC data or by future measurements at EICs.

Analogously as for the charmonium photoproduction off protons, the right panel of Fig. 2 nicely demonstrates how D-wave effects are boosted in the $\psi'(2S)$-to-$J/\psi(1S)$ cross section ratio for charmonium coherent production in UPC. Such an undesirable $\sim 20 \div 25\%$ enhancement of this

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ratio can be recognized by new, more precise data from the LHC. Here we would like to note that the onset of a negative role of D-wave effects is even stronger in production of $3S$-radially excited charmonia due to two-node structure of the corresponding wave function as was pointed out in Ref. [3].

4. Conclusions

The unjustified photon-like structure of $V \to Q\bar{Q}$ vertex leads to undesirable modification of cross sections in quarkonium photoproduction off protons and nuclei. Our observations are the following:

- The photon-like quarkonium vertex leads to an undesirable D-wave admixture in quarkonium wave functions with the relative weight, which cannot be justified by any reasonable nonrelativistic $Q - \bar{Q}$ potential model.
- The negative role of D-wave effects, falsifying our predictions slightly for photoproduction of $J/\psi(1S)$, is rather small and cannot be entirely recognized by future more precise measurements at the LHC or by planned experiments at EICs.
- The onset of D-wave effects is stronger in photoproduction of radially-excited states due to a nodal structure of corresponding radial wave functions.
- The effective way for the elimination of D-wave contribution in predictions for photoproduction cross sections is based on the study of $\psi'(2S)$-to-$J/\psi(1S)$ cross section ratio allowing to reduce theoretical uncertainties inherent in the LF color dipole formalism. Here we predict a sizeable undesirable $\sim 20 \div 25\%$ enhancement of this ratio which can be identified soon by the forthcoming ALICE data at the LHC.
- More precise data from the future EICs can help to confirm the preference of the scenario II without D-wave effects and, consequently, to rule out the photon-like structure of the quarkonium $V \to Q\bar{Q}$ transition frequently used in the literature.

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