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Remarks on charmonium production in ultra-peripheral collisions

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A B S T R A C T

In this contribution we discuss the production of charmonium states in two and three photon fusion processes in nucleus - nucleus collisions at the CERN Large Hadron Collider (LHC) energies. In a previous work we showed that the experimental study of these processes is feasible and they can be used to constrain the theoretical decay widths and give information on the non $c-\bar{c}$ component of these states. Here we discuss some points which were not addressed in that work.

1. Introduction

It is possible to study charmonium states in ultra-peripheral heavy ion collisions (UPCs) (for reviews see Ref. [1,2]). In these collisions the two nuclei do not overlap. Since there is no superposition of hadronic matter, the strong interaction is suppressed and the collision becomes essentially a very clean electromagnetic process almost without hadronic background. The few produced particles are mostly in the central rapidity region. In UPCs we do not expect to see produced particles at very large rapidities. Experimental results at the LHC [3–6] have shown that the study of photon induced interactions in hadronic collisions is feasible.

Many of the new charmonium states are exotic [7–9], i.e., they are states in which the minimum quark content is $c\bar{c}q\bar{q}$. In some cases, the exotic nature is manifest, as in the case of the charged exotic states [9]. In some other cases the multiquark nature is still under debate.

One of the main questions is: how are these quarks organized? Do they form compact objects of the size of a meson (tetraquarks)? Or are they meson molecules of the size of the deuteron? Exotic states can also be mixtures. There may be charmonium-tetraquark [10], charmonium-molecule [11] or tetraquark-molecule mixtures. In the studies of the well-known exotic charmonium $\chi_{c1}(3872)$, the $c\bar{c}$ component of the mixture required to explain the data was found to be quite large. The production of $\chi_{c1}(3872)$ in proton-proton collisions in the pure molecular approach was studied in [12–14], in the pure tetraquark model in [15] (and later in [16]) and in the charmonium-molecule mixture approach in [11].

The study of the production of exotic states started in B factories [17], went to hadron colliders and very recently [18] exotic states were observed in central nucleus-nucleus collisions. We believe that they may be also seen in ultra-peripheral collisions.

In [19] we have updated and completed the calculation of the cross sections for charmonium production in two and three photon fusion processes in UPCs started in [20]. In this note we will present some complementary calculations and also some consistency checks. In the next section we compare the results of two equivalent approaches, which should in principle yield the same results: classical fields and equivalent photons. In Section 3 we compare the cross sections for C-odd mesons obtained with three photon fusion and with photon-Pomeron fusion. In Section 4 we address vector states whose nature is still under debate. We compute their production cross section as $c-\bar{c}$ states in three-photon fusion processes. In the last section we present our conclusions.

2. Classical field versus equivalent photons

In UPCs with heavy nuclei, the number charges is very large. These charges are sources of electromagnetic fields, which are so intense that they can be treated classically. In this environment, the production of a fermion-antifermion pair is described by Feynman diagrams with an external field A_μ. This formalism was first proposed in [20]. Alternatively, one can use the equivalent photon approximation (EPA), also called Weizsäcker-Williams method, in which the virtual photons in the field are replaced by an equivalent field of real photons. In [20], it was shown that, under certain assumptions, the two methods are equivalent and yield the same results for the cross sections of C-even meson production. However no concrete numerical comparison was made. This is going to be done in what follows.

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2.1. Charmonium production from classical fields

In the classical field approximation (CFA), the cross section for the production of C-even mesons is given by [20]:

$$\sigma = \frac{16(2J+1)}{\pi^2}\frac{Z^4\alpha^2}{M^3}\frac{\Gamma_{\gamma\gamma}}{E}\int dP_z d\mathbf{q}_{1t} d\mathbf{q}_{2t} \frac{(\mathbf{q}_{1t}\times\mathbf{q}_{2t})^2\ \left[F_1(q_{1t}^2)F_2(q_{2t}^2)\right]^2}{\left(q_{1t}^2+\omega_1^2/\gamma^2\right)^2\left(q_{2t}^2+\omega_2^2/\gamma^2\right)^2} \quad (1)$$

where P_z, E, M and J are the longitudinal momentum, energy, mass and spin of the produced meson, respectively; $\Gamma_{\gamma\gamma}$ is the two-photon decay width of the meson; Z, α and γ are the atomic number, the fine structure constant and the Lorentz factor. Finally, F_1 and F_2 are the projectile and target form factors. Following [20] it is easy to relate the meson variables with the "photon energies" ω_1 and ω_2 (actually, these are the energies taken from the field A_μ in two different points):

$$E = \omega_1 + \omega_2 \quad P_z = \omega_1 - \omega_2 \quad \frac{M^2}{4} = \omega_1\omega_2$$

The photon energies ω_1 and ω_2 are related to the mass M and the rapidity Y of the outgoing meson by

$$\omega_1 = \frac{M}{2}e^{Y} \quad \omega_2 = \frac{M}{2}e^{-Y}$$

In [19] we used the nuclear form factor proposed in Ref. [21], which can be calculated analytically as

$$F = \frac{4\pi\rho_0}{A q^3}\left[\sin(qR) - qR\cos(qR)\right]\left[\frac{1}{1+q^2a^2}\right]. \quad (2)$$

For Pb we used $R = 6.63$ fm and $a = 0.549$ fm, with ρ_0 normalized so that $\int d^3r\rho(r) = 208$ [22].

During the derivation of (1), we had to use a prescription to bind together the produced quark and antiquark into a bound state. We did this using the projection operators [20]

$$\bar{u}\cdots v \longrightarrow \frac{\Psi(0)}{2\sqrt{M}}\,\mathrm{tr}\left[\cdots(\not{P}+M)i\gamma^5\right]$$
$$\bar{u}\cdots v \longrightarrow \frac{\Psi(0)}{2\sqrt{M}}\,\mathrm{tr}\left[\cdots(\not{P}+M)i\not{\hat{e}}^*\right] \quad (3)$$

where $\cdots$ denotes any matrix operator. The first equation describes the production of spin 0 and the second describes the production of spin 1 particles, respectively. The quantity $\Psi(0)$ denotes the bound state wavefunction calculated at the origin, $\mathbf{r} = 0$, and $\hat{e}^*$ is the polarization vector of the outgoing vector meson. Squaring the corresponding amplitude yields the factor $|\Psi(0)|^2$, which is then related to the decay width $\Gamma_{\gamma\gamma}$ through the formula derived by Van Royen and Weisskopf in Ref. [23] (see the discussion in [20]) for fermion-antifermion annihilation. Hence, because of the hadronization prescription, the cross section formulas derived in [20] apply to quark-antiquark states. Nevertheless, in order to obtain a first estimate we shall use the Van Royen - Weisskopf formula also for states, which may be multiquark states.

2.2. Charmonium production in the equivalent-photon approximation

Using the equivalent photon approximation for the UPC of two hadrons, h_1 and h_2, we obtain the cross section for the production of a generic charmonium state, R, given by

$$\sigma = \int n\left(\omega_1, \mathbf{b}_1\right) n\left(\omega_2, \mathbf{b}_2\right) \hat{\sigma}\left(\gamma\gamma \to R\right) \mathrm{d}^2\mathbf{b}_1 \mathrm{d}^2\mathbf{b}_2 \mathrm{d}\omega_1 \mathrm{d}\omega_2 \quad (4)$$

The quantity $n(\omega_i, b_i)$ is known as the equivalent photon spectrum generated by the hadron (nucleus) i, and $\sigma_{\gamma\gamma\to R}(\omega_1,\omega_2)$ is the cross section for the production of a state R from the fusion of two real photons with energies ω_1 and ω_2. Besides, in Eq. (4), ω_i denotes the energy of the photon emitted by the hadron (nucleus) h_i at an impact parameter, or distance, b_i from h_i. We adopt the equivalent photon flux expression given by

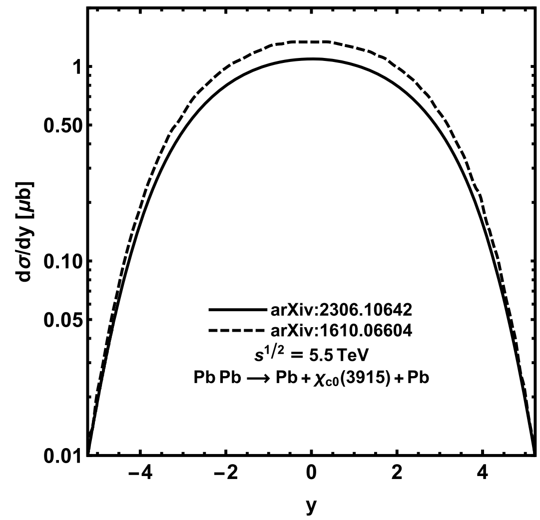

Fig. 1. Cross section for the production of $\chi_{c0}(3915)$. The solid (dashed) line shows the results obtained with classical field (equivalent photon) approximation.

$$n(\omega, b) = \frac{Z^2\alpha_{em}}{\pi^2}\frac{1}{b^2\omega}\times \left[\int u^2 J_1(u) F\sqrt{\frac{(b\omega/\gamma)^2+u^2}{b^2}}\frac{1}{(b\omega/\gamma)^2+u^2}du\right]^2 \quad (5)$$

where F is the nuclear form factor of the equivalent photon source. In order to estimate the $h_1\,h_2 \to h_1\,h_2\,R$ cross section one needs the $\gamma\gamma \to R$ production cross section as input. Usually one uses the Low formula [24], where the cross section for the production of the R state in two-photon fusion reactions is given in terms of the two-photon decay width of R,

$$\sigma_{\gamma\gamma\to R} = \pi^2(2J+1)\frac{\Gamma_{R\to\gamma\gamma}}{M_R}\delta(4\omega_1\omega_2 - M_R^2), \quad (6)$$

where the decay width $\Gamma_{R\to\gamma\gamma}$ is either taken from experiment or estimated theoretically. In the above formula, M_R and J are the mass and spin of the produced state, respectively.

Having described the two ways to calculate the resonance production cross section, we compare the numerical results obtained with the two approaches. As an example, we choose the 0^{++} state $\chi_{c0}(3915)$. Since the total cross section has been already calculated in [25], in the EPA approach, and in [19], in the CFA, we present in Fig. 1 the differential cross section $d\sigma/dY$ computed with the two approaches. As it can be seen, the two approaches yield curves which are very close to each other. The discrepancy between the curves is less than 10% and can be associated with numerical inputs.

3. Three photon fusion versus photon Pomeron interactions

Let us consider Pb-Pb UPCs at $\sqrt{s_{NN}} = 5.5$ TeV. In this case, vector charmonium production from photon-Pomeron (pP) fusion has cross sections of the order of milibarns [26–28] whereas vector charmonium production from three photon fusion (3pf) has a typical cross section of less than one microbarn [20] and is of the order of the light-by-light (LBL) scattering cross section measured by ATLAS and CMS. LBL identification was possible after a careful background subtraction, which included several kinematical cuts. Similar techniques and cuts could be

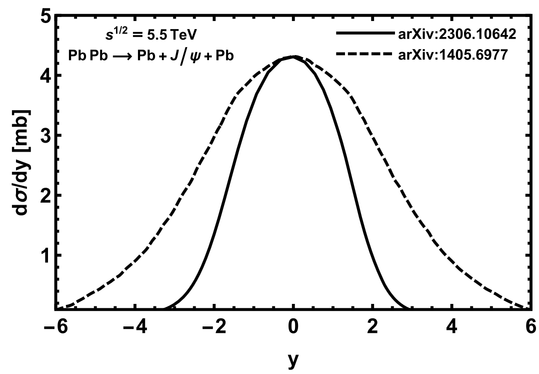

Fig. 2. Rapidity distributions of J/ψ obtained through three-photon fusion (solid line) and photon-Pomeron fusion (dashed line).

Table 1
Cross sections for production of C-odd mesons in Pb-Pb ultra-peripheral collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The decay widths are taken from the PDG [29].

State	Mass	$\Gamma_{e^+e^-}$ [keV]	σ [nb]
ρ^0	770	6.77	2466.9
ω	782	0.6	215.3
J/ψ	3097	5.3	476.5
$\psi(2S)$	3686	2.1	161.4
$\psi(3770)$	3770	0.26	19.5
$\psi(4040)$	4040	0.86	59.7
$\psi(4160)$	4160	0.48	32.4
$\psi(4230)$	4230	1.53	101.5
$\psi(4415)$	4415	0.58	36.9

used to discriminate between pP and 3pf vector charmonium production. Similar considerations apply to the production of scalar and tensor charmonium states, where we need to distinguish photon-photon fusion from Pomeron-Pomeron fusion.

The first step, addressed in [19], is to determine the order of magnitude of the total cross section. The second step is to determine the region of the phase space where 3pf dominates. In what follows we start this investigation, calculating the rapidity distribution of J/ψ produced through 3pf and comparing it the rapidity distribution resulting from pP processes.

In Ref. [20] we derived the expression for the cross section of three-photon fusion into a C-odd meson. It reads:

$$\sigma = 1024\,\pi \left|\Psi(0)\right|^2 (Z\alpha)^6 \frac{1}{M^3 E} \times \int dP_z \frac{dq_{1t}\, q_{1t}^3\, \left[F(q_{1t}^2)\right]^2}{\left(q_{1t}^2 + \omega_2^2/\gamma^2\right)^2} \times \int \frac{dq_{2t}\, q_{2t}\, \left[F(q_{2t}^2)\right]^2}{\left[q_{2t}^2 + (2\omega_1 - \omega_2)^2/\gamma^2\right]^2} \times \left[\int \frac{dk_t\, k_t\, F(k_t^2)}{\left(k_t^2 + (\omega_1 - \omega_2)^2/\gamma^2\right)}\right]^2 \quad (7)$$

The definitions of the variables are as in (1). However, in the present case, the wave function $|\Psi(0)|^2$ can no longer be related to the $\gamma\gamma$ decay width. On the other hand, vector mesons can decay into e^+e^- pairs and the corresponding decay widths are well known experimentally. Using a similar derivation as for the $\gamma\gamma$ decay, the e^+e^- decay width of the vector mesons was found to be proportional to the wave function squared [23], i.e. $\Gamma_{e^+e^-} \propto |\Psi(0)|^2$.

Eq. (7) can be differentiated with respect to P_z and then through a change of variables can be converted into a rapidity distribution. We choose to calculate the J/ψ rapidity distribution and compare it with the equivalent distribution computed for the pP process, published in Ref. [28]. The two distributions are shown in Fig. 2. The 3p curve (solid line) was multiplied by a large and arbitrary factor so that the maxima of the two curves coincide. If these maxima would be located in different positions, or if the width of the 3p curve would be much larger than the pP one, there would be a chance to separate the 3p process from the huge pP background. Unfortunately, this seems not to be the case.

4. Vector $c - \bar{c}$ or multiquark states?

In this section we focus on $c - \bar{c}$ vector states, giving special attention to the states, which are presently quoted by the PDG [29] as $c - \bar{c}$, but whose nature is still under debate and which might still be multiquark states, or at least, might have a multiquark (either tetraquark or molecular) component.

In Ref. [19] we computed the charmonium production cross sections using the formulas for conventional c-$\bar{c}$ described in the previous section. All the ingredients of the calculation were fixed and the formalism (developed in [20]) was appropriate to the study of conventional quark-antiquark states. The results obtained in [19] may serve as baseline for the experimental searches in UPCs. If there are large discrepancies between data and our numbers, this will indicate the existence of a molecular or tetraquark component.

In Table 1 we present the cross sections for vector charmonium production. The first four lines are just an update of the results found in [20]. The other lines present states which may be exotic. A common feature shared by all these ψ states (with the exception of $\psi(3770)$) is that they are all above a $D\bar{D}$ threshold and yet this decay mode is not a dominant one. This fact (among other things) raises the suspicion that these are not conventional $c\bar{c}$ states.

4.1. $\psi(3770)$

The nature of the $\psi(3770)$ resonance is still a subject of debate. Initially, it has been regarded as the lowest-mass D-wave charmonium state above the $D\bar{D}$ threshold, i.e. a pure $c\bar{c}$ meson in the quark model. However, in Ref. [30] it was suggested that the $\psi(3770)$ may contain a considerable tetraquark component. In that work it was also suggested that the tetraquark nature of the state would reveal itself in the decay $\psi(3770) \to \eta J/\psi$ and a prediction of the decay width in this channel was given. Very recently, this decay was observed by the BESIII collaboration [31] and the measured width was close to the prediction made in [30], giving support to the possible tetraquark component of the $\psi(3770)$. In our formalism, we treat the vector mesons as $c\bar{c}$ bound states. So our predicted cross section refers to the production of a conventional charmonium or to the charmonium component of the mixed charmonium-tetraquark state.

4.2. $\psi(4160)$ *and* $\psi(4230)$

The $\psi(4160)$ and $\psi(4230)$ have the same quantum numbers with a mass difference approximately equal to 40 MeV but can hardly be described within the quark model at the same time [32]. The $\psi(4160)$ is considered as a 2^3D_1 $c\bar{c}$ state due to its consistency with the predictions of the quark potential model [32]. Furthermore, while the $\psi(4160)$ appears in the open charm channels, it is not present in the hidden-charm channels, and the decay channels of $\psi(4230)$ appearing in the PDG table are mostly due to hidden-charm channels. Clearly, these states deserve further studies. In [33] it has been argued that the $\psi(4160)$ and $\psi(4230)$ are in fact the same state. The measurement of the production cross sections of these two states in the three photon fusion may help elucidating their nature.

5. Conclusion

In Ref. [19] we studied charmonium production in UPCs at LHC energies due to two and three photon fusion processes. We used the QED formulas (derived in [20]) complemented with the experimental data on decay widths. We predicted sizable values for the cross sections in Pb-Pb collisions. Here we extended the discussion presented in [19]. We checked that the CFA and the EPA are equivalent also from the practical point of view. We found that the rapidity distributions obtained in 3pf and pP processes have a similar shape, what makes the measurement of 3pf even more challenging. Our conclusion is that the experimental study of charmonium production in UPCs is difficult but worth pursuing. It will be valuable to constrain decay widths calculated theoretically and, ultimately, it will help in determining the structure of the charmonium states, confirming or not their quark-antiquark nature.

CRediT authorship contribution statement

R. Fariello: Conceptualization. **F.S. Navarra:** Funding acquisition. **C.A. Bertulani:** Writing – original draft. **D. Bhandari:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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