Color evaporation and elastic $Y$ photoproduction at DESY HERA

M. B. Gay Ducati*  
Instituto de Física, Universidade Federal do Rio Grande do Sul, Caixa Postal 15051, Cédigo de Enderecamento Postal 91501-970, Porto Alegre, RS, Brazil

V. P. Gonçalves†  
Instituto de Física e Matemática, Universidade Federal de Pelotas, Caixa Postal 354, Cédigo de Enderecamento Postal 96010-090, Pelotas, RS, Brazil

C. B. Mariotto‡  
Instituto de Física, Universidade Federal do Rio Grande do Sul, Caixa Postal 15051, Cédigo de Enderecamento Postal 91501-970, Porto Alegre, RS, Brazil

*Email address: gay@if.ufrgs.br
†Email address: barros@ufpel.tche.br
‡Email address: mariotto@if.ufrgs.br

The diffractive photoproduction of vector mesons is usually described by considering the two-gluon (Pomeron) exchange, the nondiagonal parton distributions, and the contribution of the real part to the cross section. In this Brief Report we analyze the diffractive photoproduction of the $Y$ at DESY HERA using an alternative model, the color evaporation model (CEM), where the cross section is simply determined by the boson-gluon cross section and an assumption for the production of the colorless state. We verify that, as in the $J/\psi$ case, the HERA data for this process can be well described by the CEM. Moreover, we propose the analysis of the ratio $R=\sigma_{Y}/\sigma_{J/\psi}$ to discriminate between the different approaches.

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The successful operation of the DESY $ep$ collider HERA has opened a new era of experimental and theoretical investigation into diffractive vector-meson photo- and leptoproduction. On the experimental side, the HERA accelerator extends the accessible energy range by more than one order of magnitude over previous experiments. The HERA data show that the cross sections for exclusive vector-meson production rise strongly with energy when compared to fixed-target experiments, if a hard scale is present in the process. On the theoretical side, vector-meson production has proved to be a very interesting process in which to test the interplay between the perturbative and nonperturbative regimes of QCD.

For a review, see, for example, [1]. While in an inclusive process, such as open heavy flavor production, the cross section is described in terms of a perturbative term associated with the cross section of the partonic subprocess and a nonperturbative term represented by the parton distributions, an analogous factorization of hard and soft physics does not apply to quarkonium production rates [2], which constitute a small fraction of the total open flavor cross section. This makes quarkonium physics a challenging field [2].

The current picture used in the literature to describe the diffractive photo- and leptoproduction of vector mesons assumes that the color singlet property of the meson is enforced at the perturbative level by two-gluon (Pomeron) exchange [3]. In this approach the amplitude, in the target rest frame, is factorized as a sequence of events very well separated in time: (i) the photon fluctuates into a quark-antiquark pair, (ii) the $q\bar{q}$ pair scatters on the proton target, and (iii) the scattered $q\bar{q}$ pair turns into a vector meson. The interaction is mediated by the exchange of two gluons in a color singlet state. Moreover, the two-gluon exchange amplitude can be shown to be proportional to the gluon distribution $xg(x,\hat{Q}^2)$, with $x=(M^2+Q^2)/W^2$ and $\hat{Q}^2=\frac{1}{4}(M^2+Q^2)$, where $W$ is the $\gamma p$ center of mass energy and $M$ is the invariant mass of the $q\bar{q}$ system. In the case of the production of a heavy meson, the presence of the heavy meson mass ensures that perturbative QCD can be applied even in the photoproduction limit. This approach has been improved, particularly regarding the role of the vector-meson light cone wave function [4], and describes reasonably the HERA $J/\psi$ data. When applied to the recent HERA $Y$ data [5,6], it reproduces the data only if new effects, with significant contributions are considered [7,8]: (a) the nondiagonal parton distributions, which probe new nonperturbative information about hadrons and are a generalization of the conventional parton distributions (for a review see Ref. [9]); and (b) the real part of the scattering amplitude. In Ref. [8], a strong correlation between the mass of the diffractively produced state and the energy dependence of the total cross section was found, implying a distinct energy dependence for the $Y$ and $J/\psi$ photoproduction. One of the main motivations for the study of diffractive photoproduction of vector mesons in the Pomeron model is the possibility of obtaining a sensitive probe of the behavior of the gluon distribution, due to the quadratic dependence on the gluon distribution [3,10] of the cross section in this model.

An alternative view of the diffractive photoproduction process was proposed recently in Ref. [11], where the $J/\psi$ photoproduction was analyzed using the color evaporation...
model (CEM) [12]. In this case the color singlet is not
enforced at the perturbative level and the cross section for
the process is given essentially by the boson-gluon cross section
plus an assumption for formation of the colorless meson. In
the CEM for diffractive photoproduction the cross section is
linearly proportional to the gluon distribution. The authors of
Ref. [11] obtained a parameter-free prediction which de-
scribes the HERA J/ψ data very well.

In this Brief Report we extend the application of the CEM
to the recent HERA Y data and verify that, using the param-
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ablely describes the experimental data with no need to intro-
duce a colorless (Pomeron) exchange at the perturbative
level, or the nondiagonal parton distributions or the con-
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Let us start with a brief review of the color evaporation
model. One of the main uncertainties in quarkonium produc-
tion comes from the different approaches.

Considering the elastic photoproduction, this model reason-
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the $\rho$ factors by the simple relation $F_i = 1/9 \rho_i$, where the 1/9 is the probability of having the $b\bar{b}$ pair in a color singlet state after the soft gluon exchanges, and $\rho_i$ are the universal factors that give the fractions of the onium cross section carried by the different onium states. Their corresponding values are, from above,

$$\rho^d[Y] = 0.207, \quad \rho^d[Y'] = 0.18, \quad \rho^d[Y''] = 0.066.$$  \hfill (3)

Once the free parameters have been determined in the hadronic processes, we can use the CEM to predict the $Y$ photoproduction at HERA. This also follows the assumption used in [5] that the production ratios of $Y$, $Y'$, and $Y''$ are the same as those measured in hadron-hadron collisions. A comment is in order here. In Ref. [17] the $Y$ hadroproduction was calculated considering the next-to-leading order contributions for the cross section, which implies that the factor $F$ determined from data does not contain perturbative contributions beyond leading order and can be considered a universal factor that describes the probability for quarkonium production. Moreover, the calculations in Ref. [17] used the Martin-Roberts-Stirling set D$^{-}$ (MRS D$^{-}$) parton densities as input, but, as demonstrated in [18], where an update from the analysis of the $Y$ suppression for the compact muon solenoid (CMS) detector was made, the $Y$ data can be equally well described using the 1994 Glück-Reya-Vogt (GRV 94) LO [19] parton densities.

The cross section $\sigma[bb]$ is computed at leading order using the GRV 94 LO [19] parton densities with $m_b = 4.75$ GeV, $m_b = 5.279$ GeV, and the renormalization and factorization scales set to $\mu = (M_{Q\bar{Q}})^{1/2}$ [12,11], with $Q = b$. In Fig. 1 we show our predictions for $Y$ photoproduction at HERA energies. Both the total $Y + Y' + Y''$ and direct $Y$ production are presented, since the cross sections measured by the ZEUS and H1 Collaborations did not select the direct $Y$ state, but rather the data were integrated over an interval of the $\mu^+\mu^-$ mass that includes at least the $Y$, $Y'$, and $Y''$ resonances. We verify that the current experimental data do not allow us to discriminate between the distinct contributions. We emphasize that our results are completely parameter-free and that the CEM reasonably describes the scarce experimental data.

The simplicity of the CEM strongly contrasts with the number of assumptions necessary in the Pomeron models to describe the same set of data. Here we propose a signature to discriminate between these models. As we quoted above, the Pomeron models predict a stronger growth in energy for the diffractive $Y$ photoproduction than for $J/\psi$ photoproduction, due to the strong correlation between the mass of the diffractively produced state and the energy dependence of the cross section. In contrast, in the CEM the growth of the cross section is directly determined by the gluon distribution $xg(x,\mu)$, where $\mu$ is the factorization scale. Therefore, the energy dependence of the ratio

$$R_{CEM} = \frac{\sigma_Y}{\sigma_{J/\psi}}$$  \hfill (4)

can be used to discriminate between the models.

As an intermediate step to calculate the rate mentioned, we show in Fig. 2 our previous calculation of $\sigma_{J/\psi}$, contrasted with the more recent HERA data [6]. We see that these data can be reasonable explained without tuning the parameters, which were taken as those previously used in Ref. [11]. This gives one more clue that the CEM can be used to explain elastic $J/\psi$ photoproduction.

In Fig. 3 we present the energy dependence of the ratio $R_{CEM} = \sigma_Y / \sigma_{J/\psi}$ calculated using the CEM, where $\sigma_Y$ repre-
The original motivation for the study of diffractive photoproduction was the possibility of extracting the gluon distribution inside the proton. However, the dependence on the gluon distribution is one of the major differences between the descriptions of the diffractive photoproduction using the Pomeron model and the CEM. Whereas the Pomeron model has a quadratic dependence on $x_g$, this dependence is linear in the CEM. Our result demonstrates that, before extracting the gluon distribution from HERA $Y$ and $J/\psi$ data, one should determine the correct description for this process, for example, by measuring the energy behavior of the $\sigma_Y/\sigma_{J/\psi}$ ratio.

The CEM describes a large range of data in hadro- and photoproduction, as shown in Refs. [12,11,20]. Using this model, in this Brief Report we obtain a parameter-free description of the elastic $Y$ photoproduction at HERA energies. We verify that this simple model reasonably describes the experimental data, similarly to the Pomeron models. As a distinct feature between these models, the CEM predicts a softer energy dependence of the ratio between the $Y$ and $J/\psi$ cross sections. Of course, when more precise data become available, discrimination between these models should be possible, which will allow us to decide whether the CEM is only an alternative phenomenological model for the current energies or whether it contains some underlying nonperturbative dynamics that is important in both diffractive and nondiffractive quarkonium production. In the latter case, more theoretical studies will be necessary to understand the soft interactions in the process of color neutralization.

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