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Photoproduction of Quarkonium From Soft Color Exchanges

J. Rathsman [ab]

[a] Stanford Linear Accelerator Center,
Stanford University, Stanford, CA 94309

[b] Dept. of Radiation Sciences,
Uppsala University,
Box 535,
S-751 21 Uppsala, Sweden

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Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

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Photoproduction of Quarkonium from Soft Colour Exchanges*

J. Rathsman[ab]

[a] Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309, USA
[b] Dept. of Radiation Sciences, Uppsala University, Box 535, S-751 21 Uppsala, Sweden

Abstract: We discuss photoproduction of quarkonium states in the models of soft colour interactions and the generalised area law for colour string reinteractions as implemented in the Monte Carlo program AROMA.

The physics of heavy quarks offers many probes for a better understanding of the interplay between perturbative and non-perturbative aspects of quantum chromodynamics. One such question is the production mechanisms for quarkonium states for which a complete understanding is not available presently. (For a recent review over different mechanisms for quarkonium production see [1].) The colour octet model [2] can describe the large direct production of J/ψ's and ψ''s at the Fermilab Tevatron [3], which is a factor of ~ 30 above expectations from the colour singlet model [2], but it does not seem to describe the polarisation correctly [4]. In addition it does not seem to be consistent with data from HERA which agrees quite well with the colour singlet model [5, 6].

This note will discuss the elastic and inelastic photoproduction of quarkonium states in the models of soft colour interactions (SCI) [7] and the generalised area law for colour string reinteractions (GAL) [8]. The SCI model has been shown to be able to describe the quarkonium cross-sections observed at the Fermilab Tevatron [9] and therefore it is also of interest to compare it with data from HERA. The GAL model, which can be viewed as an refinement of the SCI model, has not previously been applied to quarkonium production.

The common basic assumption for these two models is that there are soft colour exchanges in the final state which converts heavy quark pairs in a colour octet state into a colour singlet state. If the invariant mass of the quark pair is below the threshold for open charm production it will produce a bound quarkonium state. It is also assumed that the soft colour exchanges which lead to quarkonium production, factorises from the hard interaction which can be described by perturbative methods.

The models have been implemented in the Monte Carlo program AROMA [10] which contains the leading order matrix elements for photo- and electroproduction of heavy quarks through the boson gluon fusion process. Softer QCD radiation (but still perturbative) is taken into

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account by the initial and final state parton showers. This gives a partonic final state, with a colour topology given by the planar approximation, which is normally hadronised using the Lund string model [11]. The models for soft colour exchanges alters the colour topology of the events before the hadronisation and can thus produce quarkonium states.

The basic assumption of the SCI model is that perturbatively produced partons have soft colour exchanges with the background colour field of the incoming hadron or hadrons. These colour exchanges change the colour topology of an event as illustrated in Fig. 1. The probability for a soft colour exchange depends on the non-perturbative dynamics and is thus not easily calculated. For simplicity it is therefore assumed to be a constant, $R_{\text{SCI}} = 0.5$, in the SCI model. Furthermore it is assumed that the momentum exchanged can be neglected (for more details on the SCI model see [7]). Apart from the successful description of quarkonium production at the Tevatron, the SCI model also explains the large deep inelastic cross-section for events with a large rapidity gap [7]. In addition the model describes other diffractive phenomena like diffractive W-production at the Tevatron [12, 13].

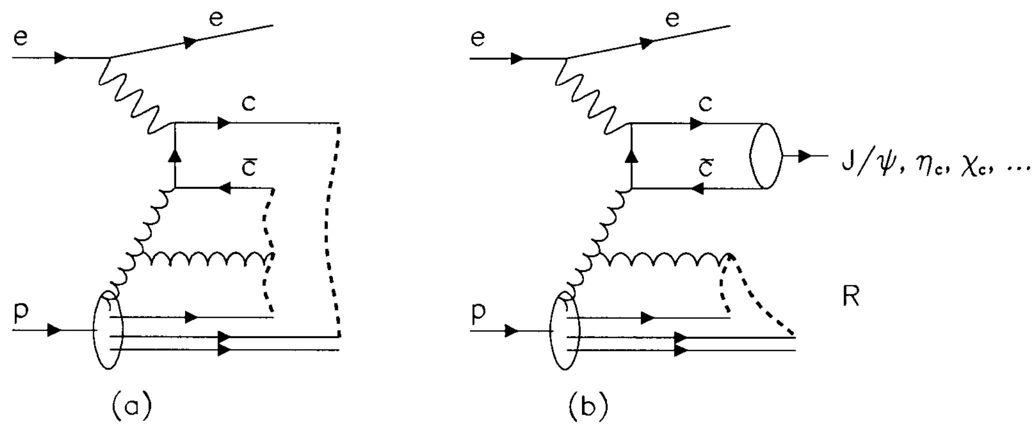

Figure 1: *Examples of how soft colour exchanges as described by the SCI and GAL models can modify the colour topology and give quarkonium states. (a) shows the "ordinary" planar topology which is normally assumed. (b) shows an alternative colour topology after the application of the SCI or GAL model where the $q\bar{q}$ pair is in a colour singlet state. If the invariant mass of the $q\bar{q}$ is below the threshold for open charm production it will form a quarkonium state.*

The generalised area law for colour string reinteractions (GAL) is similar in spirit to the SCI model in that it is a model for soft colour exchanges. The main difference is that the GAL model is formulated in terms of interactions between the strings connecting the partons produced in an event. In addition, the probability for an interaction is not constant as in the SCI model but there is a suppression factor which depends on the area difference between the two alternative string-configurations. The probability for a string reconnection is given by $R_{\text{GAL}} = 0.1\exp(-b\Delta A)$ where $b = 0.45$ GeV^{-2} is one of the hadronisation parameters in the Lund model and ΔA is the area difference (for more details see [8]).

Another difference between the GAL and SCI models is that the GAL model is applicable for all hadronic final states, *i.e.* it is also valid for e^+e^- annihilation, whereas the SCI model is only applicable for reactions with an initial hadron[1]. The GAL model has been successfully

[1]In principle the SCI model could be extended to include e^+e^- annihilation but this would require a retuning of the hadronisation parameters. See [14] for a more detailed discussion.

tuned to data from e^+e^- annihilation and by comparing with the JETSET Monte Carlo [8]. At the same time it gives a good description of the diffractive structure function (for more details on diffractive and non-diffractive hadronic final states in deep inelastic scattering within the SCI and GAL models see [14]). The retuning of the hadronisation amounts to setting the cut-offs in the initial and final state parton showers to $Q_0 = 2$ GeV in addition to using $b = 0.45$ GeV^{-2}. One might worry that the cut-off Q_0 is relatively large compared to the default value $Q_0 = 1$ GeV. However, it is not obvious that perturbation theory should be valid for so small scales when more exclusive final states are considered. Therefore, Q_0 can be considered as a free parameter describing the boundary below which it is more fruitful to describe the fragmentation process in terms of strings instead of perturbative partons.

Both the SCI and GAL models have been implemented in the LSCI routine in the Monte Carlo program LEPTO [15] (the latest version is available on the LEPTO homepage, `http://www3.tsl.uu.se/thep/lepto`). Thereby both models are also accessible in the Monte Carlo program AROMA [10] for electro- and photoproduction of heavy quarks (see the AROMA homepage, `http://www3.tsl.uu.se/thep/aroma`). For the GAL model one also needs a new version of the LEPTO routine in LEPTO and the latest version of AROMA (for more details see, `http://www3.tsl.uu.se/thep/rathsman/gal`).

For the production of quarkonium states further assumptions are needed. In the following we give a short description of the model used which has been implemented in the LEPTO routine LSMALL that is called from within AROMA (for more details on the model see [9]). The total cross-section for quarkonium production is obtained by integrating the partonic cross-section for a colour singlet heavy quark system, obtained by applying the SCI or GAL model, from the quark threshold $2m_Q$ to the open heavy flavour threshold $2m_M$,

$$\sigma_{onium} = \int_{2m_Q}^{2m_M} \frac{d\sigma}{dm_{Q\bar{Q}}} \otimes \mathrm{SCI/GAL}\; dm_{Q\bar{Q}} \,. \qquad (1)$$

Thus the fraction of the partonic cross-section which is in a colour singlet state is not a constant, as is assumed in the colour evaporation model [2], but it depends on the parton configuration. The partial cross-sections for different quarkonium states is then obtained following [16] by using spin-statistics,

$$\sigma_X = \frac{\Gamma_X}{\sum_Y \Gamma_Y} \sigma_{onium} \qquad (2)$$

where $\Gamma_X = (2J_X + 1)/n_X$ is the weight for each state with an extra suppression $1/n_X$ of radially excited states (like the ψ'). Thus no other quantum numbers are taken into account. As a consequence a large cross-section for η_c's is predicted.

In the following we will show some illustrative results for elastic and inelastic photoproduction ($Q^2 < 4\mathrm{GeV}^2$) of J/ψ mesons by applying the two models to the event generator AROMA. As will be discussed below there are several uncertainties that effect the results so these should not be viewed as the definitive predictions of the models. The results have been obtained with default settings in the Monte Carlo except for the parton densities for which the CTEQ4L [17] set was used and for the GAL model the cut-off in the parton showers and the b parameter in the hadronisation were set to the values given above.

Fig. 2 shows the energy dependence of the total cross-section compared to data from ZEUS [5, 18] and H1 [6]. As can be seen from the figure the SCI and GAL models has a slightly different energy dependence and the normalisation is also different. Recent preliminary data [19] indicate that the elastic cross-section has the energy dependence $W^{0.8}$ which is also illustrated in the figure. Comparing with the two models we see that the GAL model has a similar energy dependence whereas SCI has a slightly softer energy dependence ($\sim W^{0.5}$ for elastic and $\sim W^{0.6}$ for inelastic).

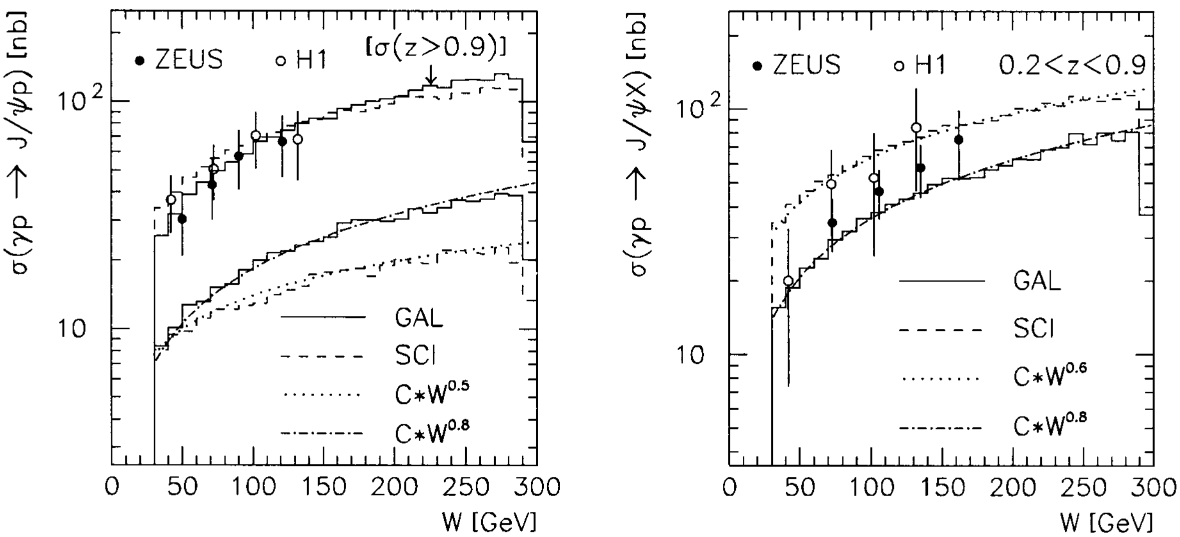

Figure 2: *Results of applying the SCI (dashed) and GAL (solid) models to the* Aroma *Monte Carlo program: the energy dependence of the cross-section for elastic (left) and inelastic (right) photoproduction of J/ψ mesons compared to data from ZEUS [5, 18] and H1 [6]. For comparison the cross-section $\sigma(\gamma p \to J/\psi X)$ for $z > 0.9$ is also shown together with the elastic cross-section to illustrate the uncertainty in the results due to the treatment of the proton remnant.*

The overall rate of charmonium production in the models depends on the parameters $R_{\rm SCI}$ and $R_{\rm GAL}$ respectively which are fixed from the diffractive structure function. Thus it would seem that normalisation of the models does not agree with data. However, the overall normalisation of the results is quite uncertain since the models are based on a leading order calculation. This means that the result is sensitive to the choice of factorisation and renormalisation scale which mainly affect the normalisation. By multiplying the leading order cross-section with a K-factor one can get the same normalisation as from a next-to-leading order calculation. These K-factors can be of the order $2-3$ for heavy quark production. Alternatively one could compare with the cross-section for open heavy flavour production.

The normalisation of the elastic cross-section is also sensitive to the treatment of the proton remnant in the Monte Carlo program which is quite uncertain. In other words the relation between proton dissociation and elastic events is uncertain and should be adjusted to data. As an illustration of this problem the cross-section $\sigma(\gamma p \to J/\psi X)$ for $z = \frac{p_{J/\psi} \cdot p}{q \cdot p} > 0.9$, which roughly corresponds to the sum of the elastic and proton dissociation cross-sections, is compared with the elastic cross-section in Fig. 2. The figure indicates that the model gives a proton dissociation cross-section which is a factor $2-4$ larger than the elastic cross-section. This should be compared with the experimental results where the two cross-sections are of similar magnitude. Thus the treatment of the proton remnant does not seem to be in accordance with data and should be modified. Given this additional uncertainty for the elastic cross-section one cannot draw any firm conclusions about the validity of the models from the apparently different normalisations of the elastic and inelastic cross-sections from the models in relation to the experimental results. Instead the data can be used to improve the models in their details.

Fig. 3 shows the $p_\perp^2$ dependence of the elastic cross-section and the in-elasticity of the inelastic cross-section, where $z = \frac{p_{J/\psi} \cdot p}{q \cdot p}$. The figure shows that for both models the shape of the $p_\perp^2$ distribution agrees quite well with data. The $p_\perp^2$ dependence in the models follows from the intrinsic $k_\perp$ distribution of gluons in the proton as discussed in [7]. Recent preliminary data [20] indicate that the $p_\perp^2$ dependence may be energy dependent which should be investigated in more detail.

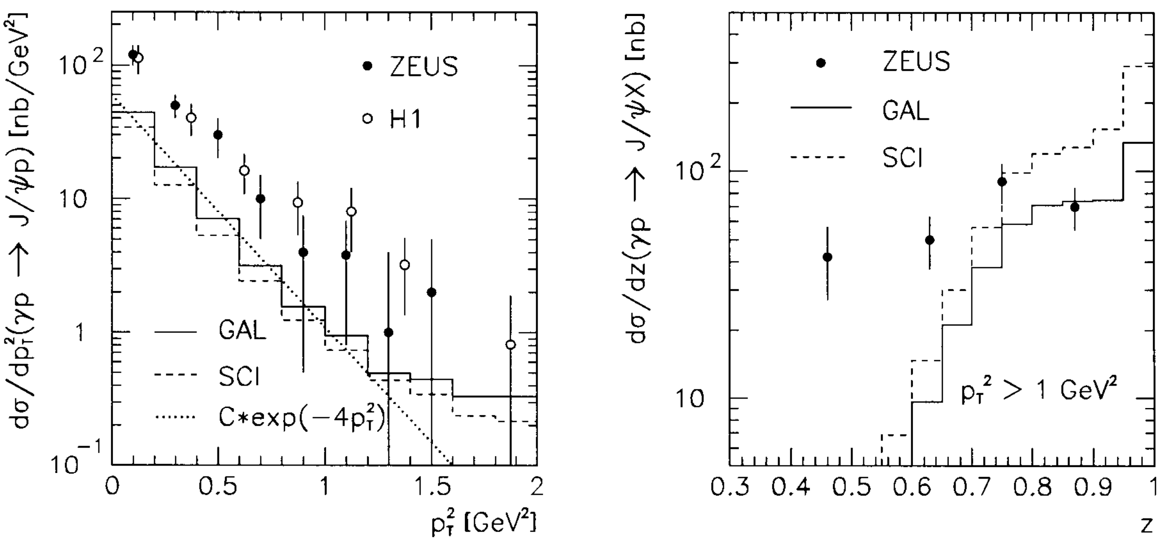

Figure 3: *Results of applying the SCI (dashed) and GAL (solid) models to the* AROMA *Monte Carlo program: the $p_\perp^2$ dependence of the elastic cross-section (left) and the in-elasticity of the inelastic cross-section (right) compared to data from ZEUS [5, 18] and H1 [6].*

From the figure it is also clear that the z-distribution in the two models does not seem to be consistent with data. However, this can be understood in the following way. The colour ordering from the parton cascade is based on the planar approximation. This means that the heavy quark pair will never be in a colour singlet state even though there are perturbative diagrams that lead to this configuration (these are the same diagrams that are used in the colour singlet model). This can partly explain the deficit for intermediate z since the perturbative gluons radiated can be quite hard. In addition, the parton showers only add softer QCD radiation which means that z is typically large.

In addition to J/ψ production the models also gives predictions for other charmonium states as well as bottomonium. The models are also applicable for electroproduction of quarkonium states. For the production of other quarkonium states there is also the question whether the assumption that spin is the only important quantum number when dividing the quarkonium cross-section onto different states is correct. This assumption also has large effects on the normalisation of the J/ψ cross-section. Another more general uncertainty is the starting and stopping scale for the parton showers. However this uncertainty should be quite small.

In summary we have shown to what extent the models for soft colour interactions and the generalised area law for colour string reinteractions can describe photoproduction of quarkonium states at HERA. We have also discussed the uncertainties in the models especially regarding normalisation and the in-elasticity distribution for the inelastic cross-section.

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