Charmonium Production at ELFE Energies

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Abstract

I discuss issues related to charmonium production, in view of physics possibilities at a 15 . . . 30 GeV continuous beam electron facility. High energy photo- and hadroproduction of heavy quarkonia presents several challenges to QCD models concerning cross sections, polarization and nuclear target dependence. Theoretical approaches based on color evaporation as well as on color singlet and color octet mechanisms have met with both successes and failures, indicating that charmonium production is a sensitive probe of color dynamics. Experiments close to charm kinematic threshold will be sensitive also to target substructure since only unusual, compact target configurations contribute. In particular, subthreshold production on nuclei should identify nuclear hot spots of high energy density. At low energies, charmonium will form inside the target nucleus, allowing a determination of $c\bar{c}$ bound state interactions in nuclear matter.

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1. Introduction

The ‘Electron Laboratory for Europe’ (ELFE) project aims at a high intensity ($I_e \simeq 30 \mu A$) continuous electron beam in the 15 ... 30 GeV energy range, to be scattered off fixed targets ranging from hydrogen to heavy nuclei [1]. Among the central physics motivations are detailed studies of hadron and nuclear wave functions through hard exclusive and (semi-)inclusive processes [2]. As it turns out, ELFE will operate in the region of charm ($c\bar{c}$) threshold, which in the case of real photons is at $E_{\gamma}^{th} \simeq 8...12$ GeV for $J/\psi, \ldots, D\bar{D}$ production on free nucleons. Charm(onium) production has proved to be a very sensitive measure of reaction mechanisms, as evidenced by order-of-magnitude discrepancies found between QCD models and data [3, 4, 5]. Furthermore, the suppression of charmonium production in heavy ion collisions is widely discussed as a potential signal for the formation of a quark-gluon plasma [6]. Here I would like to discuss some of the puzzles of charmonium production and how photoproduction close to threshold can give important new clues to production mechanisms and to hadron and nuclear structure [7].

Remarkably, the only charm photoproduction data that exists (Fig. 1) in the ELFE energy range are the $J/\psi$ measurements of SLAC [8] and Cornell [9] from 1975, which predate the discovery of open charm. These early measurements of the small near-threshold cross section $\sigma(\gamma N \rightarrow J/\psi N) \simeq 1$ nb were made possible by the experimental cleanliness of the $J/\psi \rightarrow \mu\mu$ signal. With an ELFE luminosity $L \sim 10^{35}$ cm$^{-2}$s$^{-1}$ one expects a rate of about 5 $J/\psi$ dimuon decays per second, allowing detailed measurements of threshold and subthreshold effects.

It should also be kept in mind that owing to the essentially non-relativistic nature of charmonium, each charm quark carries close to one half of the $J/\psi$ momentum. Even their relative angular momentum is determined through the quantum numbers of the charmonium state. Charmonium is thus a very valuable complement to open charm channels such as $D\bar{D}$, which furthermore are difficult to measure.

Theoretically, charmonium offers very interesting challenges. Most reliable QCD tests have so far concerned hard inclusive scattering, implying a sum over a large number of open channels. The standard QCD factorization theorem [10] does not apply when the final state is restricted by requiring the charm quarks to bind as charmonium. The application of QCD to charmonium production is thus partly an art, as evidenced by lively discussions of different approaches. It seems likely that charmonium production will teach us something qualitatively new about QCD effects in hard scattering – exactly what is not yet clear (but hopefully will be so by the time ELFE turns on!).
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Figure 1: Compilation of cross sections for the process $\gamma p \rightarrow J/\psi p$ \cite{12}. Experiments at ELFE will be in the range $E_\gamma \lesssim 25$ GeV (vertical line). The curve shows the prediction of Eq. (1) for a gluon structure function $G(x) = 3(1 - x)^5$.

2. $J/\psi$ Production at High Energies

2.1 Elastic $J/\psi$ Production

Early studies \cite{11} assumed that the charmonium cross section is proportional to the $c\bar{c}$ one below open charm ($D\bar{D}$) threshold, as given by the inclusive photon-gluon fusion process $\gamma g \rightarrow c\bar{c}$. Thus

$$\sigma(\gamma N \rightarrow J/\psi + X) = f_{J/\psi} \int_{4m_c^2}^{4m_{D}^2} \frac{dM^2}{s} G(M^2/s) \sigma_{\gamma g \rightarrow c\bar{c}}(M^2)$$

(1)

where $G(x)$ is the gluon structure function and the proportionality constant $f_{J/\psi}$ is the fraction of the below-threshold $c\bar{c}$ pairs that form $J/\psi$'s. In this ‘Color Evaporation Model’ (CEM) the color exchanges which transform the color octet $c\bar{c}$ pair into a color singlet $J/\psi$ are assumed to occur over long time and distance scales, and are described by the non-perturbative factor $f_{J/\psi}$ in Eq. (1). For the model to have predictability it is important that this factor be ‘universal’, i.e,
independent of the reaction kinematics (beam energy and charmonium momentum), and hopefully also of the nature of the projectile and target. It should be emphasized, however, that the universality of $f_{J/\psi}$ is a hypothesis which has not been demonstrated in QCD.

Assuming a constant $f_{J/\psi}$ and a ‘standard’ gluon structure function $xG(x) = 3(1 - x)^5$, Eq. (1) (with $X = N$) gives a good fit (solid line in Fig. 1) to $J/\psi$ elastic photoproduction from threshold to $E_\gamma \lesssim 300$ GeV [12]. It is not very clear what this means, however. Close to threshold the single gluon exchange picture is expected to break down (cf section 3.1). At high energy, color evaporation is expected to apply to inelastic processes, since the neutralization of color will lead to additional hadrons being produced.

![Graph showing high energy data on the process $\gamma p \rightarrow J/\psi p$](image)

Figure 2: Compilation of high energy data on the process $\gamma p \rightarrow J/\psi p$ [17], with curves of the form $W^{\delta}_{\gamma p}$ as indicated. The curves marked 'MRS' and 'GRV' are the results of QCD calculations with two-gluon exchange [13, 18], for different gluon structure functions.

A consistent QCD description of high energy elastic $J/\psi$ photoproduction involves two gluon (color singlet) exchange between the charm quark pair and the target [13]. In this approach the color dynamics of the charm quark pair is treated perturbatively, i.e., the quarks are created as a compact color singlet state which couples directly to the $J/\psi$ through the wave function at the origin. This is jus-
tified by a factorization between the hard and soft physics in this process \[14\]. The (imaginary part of the) two gluon coupling to the target resembles the gluon structure function of deep inelastic scattering, although the momenta of the two gluons are not exactly equal \[13\]. The elastic \(J/\psi\) cross section may thus be approximately proportional to the square of the gluon structure function. The high energy data (Fig. 2) on \(\gamma p \to J/\psi p\) from HERA \[16, 17\] in fact shows a considerable rise of the elastic cross section with energy, which (within the considerable error bars) is consistent with the increase of \(G(x)\) for \(x = 4m_c^2/s \to 0\) \[18\].

2.2 Color Evaporation Approach to Inelastic \(J/\psi\) Production

The difficulties of perturbative QCD models in describing the data on inelastic charmonium production (cf sections 2.3 and 2.4 below) has rekindled interest in the color evaporation model \[19, 20, 21, 22\]. It has been shown that the dependence of both charmonium and bottomonium production on the projectile energy and on the energy fraction \(x_F\) of the produced state are in good agreement with that predicted through Eq. (1) for heavy quarks below threshold. The fraction of the below-threshold heavy quark cross section which ends up in quarkonium depends on the QCD parametrization (quark mass, structure functions and factorization scale) but seems to be quite small, typically (8 . . . 10)% for charm, growing to (17 . . . 32)% for bottom \[22\]. The parameter \(f_{J/\psi}\) of Eq. (1) takes similar values in \(pp\) and \(\pi p\) reactions (0.025 and 0.034, respectively \[19\]). In photoproduction the large diffractive (elastic) peak needs to be excluded, eg, by a cut on the \(J/\psi\) momentum, after which values in the range \(f_{J/\psi} = 0.005 \ldots 0.025\) were found \[22\].

The generally good agreement of the color evaporation model with data is very significant. It shows that the essential structure of the inclusive charmonium cross section is given by that of heavy quark production at leading twist. According to the spirit of color evaporation, the heavy quarks will after their production undergo a long time-scale process of evolution to the quarkonium bound state, during which the relative distance between the quarks grows and non-perturbative gluons change the overall color of the quark pair. The normalization of the production cross section, ie, the non-perturbative parameter \(f_{J/\psi}\) in Eq. (1), is thus not necessarily related to the wave function at the origin of the charmonium bound state.

2.3 The Color Singlet Model (CSM)

The ‘Color Singlet Model’ (CSM) \[23\] describes charmonium production fully in terms of PQCD. The \(c\bar{c}\) is created with proper quantum numbers to have an overlap with the charmonium state, measured by the non-relativistic wave
function at the origin. In particular, the pair has to be a singlet of color. For inelastic \( J/\psi \) photoproduction the lowest order subprocess is \( \gamma g \rightarrow c\bar{c}g \), where the final gluon radiation ensures that the charmonium is produced with an energy fraction (in the target rest frame) \( z = E_{J/\psi}/E_{\gamma} < 1 \). For production at large \( p_\perp \gg m_c \), higher order 'fragmentation diagrams' actually give the leading contribution [24].

![Graph showing the cross section for inelastic \( J/\psi \) photoproduction \( \gamma p \rightarrow J/\psi + X \) for \( p_\perp (J/\psi) \geq 1 \) GeV as a function of the \( J/\psi \) energy fraction (in the proton rest frame) \( z = E_{J/\psi}/E_{\gamma} \). Predictions based on the color singlet and octet mechanisms are compared to data from HERA.](image)

The CSM contributions to \( J/\psi \) photoproduction have been calculated to next-to-leading order in QCD [25], with a result that is in good agreement with the data (Fig. 3). For \( \psi' \) production the CSM predicts that the \( \psi'/\psi \) cross section ratio should be proportional to the square of the wave function at the origin,

\[
\frac{\sigma(\psi')}{\sigma_{dir}(J/\psi)} = \frac{\Gamma(\psi' \rightarrow \mu\mu)}{M_{\psi'}} \frac{M_{3J/\psi}^2}{\Gamma(J/\psi \rightarrow \mu\mu)} \simeq 0.24 \pm 0.03
\]

(2)

Here \( \sigma_{dir}(J/\psi) \) excludes contributions to the \( J/\psi \) from 'indirect' channels such
as $B$, $\chi_c$ and $\psi'$ decays, and the power of mass is motivated by dimensional arguments. The photoproduction data \cite{27, 28} gives for the ratio that is uncorrected for radiative decays,

\[
\frac{\sigma(\gamma N \rightarrow \psi' + X)}{\sigma(\gamma N \rightarrow J/\psi + X)} = 0.20 \pm 0.05 \pm 0.07
\]  

(3)

The upper limit on the $\chi_{c1} + \chi_{c2}$ photoproduction cross section is about 40\% of the $J/\psi$ cross section \cite{27}. Taking into account the $O(20\%)$ branching ratio for their radiative decays into $J/\psi$ only a small fraction of the photoproduced $J/\psi$'s are due to the indirect channels, and the ratios of Eqs. (2) and (3) should be compatible, as indeed they are. It should be noted, however, that the experimental ratio (3) primarily reflects diffractive (elastic) $J/\psi$ and $\psi'$ production, which dominates in photoproduction.

In hadroproduction, where inelastic channels dominate the cross section, data on the ratio (2) is also in good agreement with the color singlet model \cite{29}. This is true also for the Tevatron data on charmonium production at large $p_\perp$ \cite{4}. Even bottomonium production is quite consistent with the analog of Eq. (2), within factor two uncertainties due to the so far unmeasured contributions from radiative decays of the P states \cite{41}.

The above comparisons suggest that the ‘nonperturbative’ proportionality factors $f$ in the color evaporation model ($cf$ Eq. (1)) actually reflect perturbative physics, i.e., the wave function at the origin as assumed in the color singlet model.

In spite of its successful predictions in photoproduction and of the ratio of $\psi'$ to $J/\psi$ hadroproduction, the CSM nevertheless fails badly, by factors up to 30 \ldots 50, for the absolute hadroproduction cross sections of the $J/\psi$, the $\psi'$ and the $\chi_{c1}$ states \cite{3, 4, 5, 29}. The discrepancies are large both in fixed target total cross section data and in large $p_\perp$ production at the Tevatron. The fixed target data moreover shows that the $J/\psi$ and $\psi'$ are produced nearly unpolarized \cite{40}, contrary to the CSM which predicts a fairly large transverse polarization \cite{29}.

The fact that the CSM underestimates charmonium hadroproduction (and predicts the polarization incorrectly), suggests that there are other important production mechanisms, beyond the CSM. The nature of those processes is not yet established. A simple mnemonic, which appears to be consistent with the observed systematics, is that the CSM works whenever no extra gluon emission is required only to satisfy the quantum number constraints. Thus, for inelastic $J/\psi$ photoproduction the lowest order process $\gamma g \rightarrow c\bar{c}g$ of the CSM has only the number of gluons which is required by momentum transfer (and the prediction is successful). In the (incorrect) CSM prediction for hadroproduction gluon emission in the subprocess $gg \rightarrow c\bar{c}g$ is needed only due to the negative charge conjugation of the $J/\psi$ (or due to Yang’s theorem in the case of $\chi_{c1}$ production). Again, for $\chi_{c2}$ the lowest order process $gg \rightarrow \chi_{c2}$ is allowed in the CSM, and the
prediction is compatible with the data (within the considerable PQCD uncertainties) [29, 31]. A polarization measurement of hadroproduced $\chi_{c2}$’s would be a valuable check of the CSM [29, 32].

Photoproduction of $\chi_c$ is an interesting test case [22, 26]. The available data [27] suggests that the $\chi_{c2}/J/\psi$ ratio is lower in inelastic photoproduction than in hadroproduction. This qualitatively agrees with the CSM, in which $P$-wave photoproduction ($\gamma g \rightarrow \chi_{c2}gg$) is of higher order than $S$-wave production ($\gamma g \rightarrow J/\psi g$), while the reverse is true for hadroproduction. With no regard to quantum numbers (as in the color evaporation model) the basic subprocess would be the same ($\gamma g \rightarrow c\bar{c}$) and the $\chi_c/J/\psi$ ratio would be expected to be similar in photono- and hadroproduction.

It has been suggested that the gluons required to satisfy quantum number constraints of the $c\bar{c}$ pair in the CSM could come from additional (higher twist) exchanges with the projectile or target [29, 33]. Although normally suppressed, these contributions might be important since they do not involve energy loss through gluon emission.

2.4 The Color Octet Model (COM)

A possible solution to some of the above puzzles has been suggested based on an analysis of nonrelativistic QCD (NRQCD) [34], and commonly referred to as the ‘Color Octet Model’ (COM) [31, 35]. In cases where, due to quantum number constraints, extra gluon emission is required in the CSM the production may be dominated instead by higher order terms in the relativistic ($v/c$) expansion of the quarkonium bound state. For $P$-wave states the inclusion of relativistic corrections is in fact necessary to cancel infrared divergencies of the perturbative expansion even at lowest order.

The $c\bar{c}$ can then be produced in a color octet state, which has an overlap with a higher $|c\bar{c}g\rangle$ Fock state of charmonium, with the emission of a soft gluon. Such contributions appear in a systematic NRQCD expansion and thus must exist. Whether they are big enough to account for the large discrepancies of the CSM in charmonium production depends on the magnitude of certain non-perturbative matrix elements of NRQCD. I refer to recent reviews [3, 36] and references therein to the extensive literature on this subject.

A number of discrepancies between the color octet model and observations suggest that it will at best provide only a partial explanation of quarkonium production.

(i) Inelastic photoproduction of $J/\psi$ is overestimated by the COM [26, 37] as seen in Fig. 3. A best estimate of the discrepancy is actually even larger than shown, since the effects of soft gluon radiation were neglected.
in fitting the octet matrix elements from the Tevatron data [38]. The photoproduction cross section can be decreased in the COM only by adding a contribution which is coherent with the production amplitude.

(ii) The COM does not explain the $p_L$-integrated (fixed target) charmonium hadroproduction data, in particular not the polarization of the $J/\psi$ and $\psi'$ and the $\chi_{c1}/\chi_{c2}$ ratio [39, 40, 41]. It has been claimed (but is by no means obvious) that the (higher twist?) corrections are bigger in the fixed target data than in the large $p_L$ cross section measured at the Tevatron, which is often taken as a benchmark for COM fits. The systematics of the anomalies is actually very similar in the two processes. The color singlet model fails by a comparable factor in both cases [4], while the (leading twist) color evaporation model successfully explains the relative production rates measured in the fixed target and Tevatron experiments [21, 22].

(iii) The $\Upsilon(3S)$ cross section exceeds the CSM predictions by an order of magnitude [4, 42]. Since the relativistic corrections are much smaller for bottomonium than for charmonium, this is hard to accommodate in the COM [10]. It has been suggested that the excess could be due to radiative decay from a hitherto undiscovered $3P$ state. As in the case of the $\psi'$ anomaly, an experimental measurement of direct $\Upsilon$ production should settle this question. The ratios of $\Upsilon(nS)$ cross sections are quite compatible with expectations based on the wave function at the origin (cf Eq. (2)), with only moderate contributions from radiative decays of $P$ states [19].

2.5 Nuclear Target $A$-Dependence

Additional clues to quarkonium production dynamics is offered by data on the nuclear target $A$-dependence [43]. In the standard parametrization

$$\sigma(A) \propto A^\alpha$$

one expects $\alpha \simeq 1$ for hard incoherent scattering, which is additive on all nucleons in the target nucleus. This behavior is verified with good precision for the Drell-Yan process of large-mass lepton pair production [14] as well as for open charm ($D$ meson) production at low $x_F$ [15]. However, for $J/\psi$ and $\psi'$ hadroproduction $\alpha \simeq 0.92 \pm 0.01$ for $0.1 \lesssim x_F \lesssim 0.3$ [16]. This suppression may be interpreted as a rescattering of the charm quark pair in the nucleus, with an effective cross section of 7 mb [3] for conversion to open charm production. Such rescattering will affect the quantum numbers of the $c\bar{c}$ pair, and should thus be considered in color singlet and octet approaches. For the color evaporation model the target dependence shows that the proportionality factor $f_{J/\psi}$ in Eq. (4) is not universal for all processes.
The nuclear suppression of $J/\psi$ and $\psi'$ production increases with $x_F$, with $\alpha(x_F = .6) \simeq .8$ [46]. This effect, which breaks leading twist factorization [47], may be due to intrinsic charm [48, 49] and involve the scattering of low momentum valence quarks [50]. Ascribing the effect to parton energy loss in the nucleus requires the $(p_\perp)$ in the rescattering to be unexpectedly large [51, 52]. The dynamics of charmonium production at large $x_F$ is analogous to the large $p_\perp$ Tevatron data due to the ‘trigger bias’ effect: In both cases the charmonium carries a large fraction of the momentum of the fragmenting particle.

In inelastic (virtual) photoproduction a nuclear enhancement of $J/\psi$ production is observed, $\alpha = 1.05 \pm 0.03$ for $x_F < 0.85$ and $p_\perp^2 > 0.4 \text{ GeV}^2$ [28, 53]. Contrary to hadroproduction, the momentum distribution of $J/\psi$ photoproduction peaks at large $x_F$. Hence an explanation in terms of energy loss is conceivable [54].

In the region of the coherent peak for $J/\psi$ photoproduction on nuclei at very low $p_\perp$ there is an even stronger nuclear enhancement. E691 [53] finds $\alpha_{coh} = 1.40 \pm 0.06 \pm 0.04$, while NMC [28] gives $\alpha_{coh} = 1.19 \pm 0.02$. If the $c\bar{c}$ pairs are compact enough not to suffer secondary interactions in the nucleus, one expects $\sigma_{coh}(A, p_\perp) \propto A^2 \exp(-cA^{2/3}p_\perp^2)$ ($c$ being a constant). Hence $\alpha_{coh} = 4/3$ for the $p_\perp$-integrated cross section, in rough agreement with the data.

As should be clear from the above, quarkonium production offers interesting challenges, which are not fully met by any one proposed mechanism. It seems likely that we are learning something about color dynamics that cannot be accessed within the standard, fully inclusive formalism of PQCD. Color exchanges to the $c\bar{c}$ evidently take place in ways not adequately described by the CSM. The importance of the NRQCD contributions (which surely are present at some level) remains to be clarified, as does the assumption by the color evaporation approach that charmonium production constitutes a universal fraction of the $c\bar{c}$ cross section below open charm threshold.

3. Production Near Kinematic Threshold

As noted in the Introduction, almost all experimental information on charmonium production is at relatively high energy. While we may hope that at least some of the puzzles discussed in the preceding section will be solved in the near future, an understanding of production near threshold will have to wait for a dedicated machine like ELFE. In the following I shall discuss some generic features of (sub-)threshold charmonium production related to the composite nature of the beam and/or target [7]. It is likely that charm production close to threshold will teach us new physics, over and beyond what is now being learnt at higher energies.

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1 Calculations of higher order perturbative, leading twist effects in heavy quark production near threshold may be found in Ref. [55].
3.1 Higher Twist Effects

At high energy the dominant contribution to hard processes comes from ‘leading twist’ diagrams, characterized by only one parton from each colliding particle participating in the large momentum transfer \( (Q) \) subprocess. Since the time scale of the hard collision is \( 1/Q \), only partons within this transverse distance can affect the process. The likelihood that two partons are found so close to each other is typically proportional to the transverse area \( 1/Q^2 \), which thus gives the suppression of higher twist, multiparton contributions.

Close to the kinematic boundary the higher twist effects are enhanced, however. Thus for \( \gamma p \rightarrow c\bar{c}p \) very near threshold, all the partons of the proton have to transfer their energy to the charm quarks within their creation time \( 1/m_c \), and must thus be within this transverse distance from the \( c\bar{c} \) and from each other. The longitudinal momentum transfer at threshold (in the proton rest frame) is \( \simeq m_c \). Hence only compact proton Fock states, with a radius equal to the Compton wavelength of the heavy quark, can contribute to charm production at threshold.

Figure 4: Two mechanisms for transferring most of the proton momentum to the charm quark pair in \( \gamma p \rightarrow c\bar{c} + X \) near kinematic threshold. The leading twist contribution (a) dominates at high energies, but becomes comparable to the higher twist contribution (b) close to threshold.

The behavior of the effective proton radius in charm photoproduction near threshold can be surmised from the following argument. As indicated in Fig. 4a, one mechanism for charm production is that most of the proton momentum is first transferred to one (valence) quark, followed by a hard subprocess \( \gamma q \rightarrow c\bar{c}q \). If the photon energy is \( E_\gamma = \zeta E_\gamma^{th} \), where \( E_\gamma^{th} \) is the energy at kinematic threshold \( (\zeta \simeq 1) \), the valence quark must carry a fraction \( x = 1/\zeta \) of the proton’s (light-cone) momentum. The lifetime of such a Fock state (in a light-cone or infinite
momentum frame) is \( \tau \simeq 1/\Delta E \), where

\[
\Delta E = \frac{1}{2p} \left[ m_p^2 - \sum_i \frac{p_{i\perp}^2 + m_i^2}{x_i} \right] \simeq -\frac{\Lambda_{\text{QCD}}^2}{2p(1-x)}
\]  

(5)

For \( x = 1/\zeta \) close to unity such a short-lived fluctuation can be created (as indicated in Fig. 4a) through momentum transfers from valence proton states (where the momentum is divided evenly) having commensurate lifetimes \( \tau \), i.e., with

\[
r_{\perp}^2 \simeq \frac{1}{p_{\perp}^2} \simeq \frac{\zeta - 1}{\Lambda_{\text{QCD}}^2}
\]  

(6)

This effective proton size thus decreases towards threshold (\( \zeta \to 1 \)), reaching \( r_{\perp} \simeq 1/m_c \) at threshold, \( \zeta - 1 \simeq \Lambda_{\text{QCD}}^2/m_c^2 \).

As the lifetimes of the contributing proton Fock states approach the time scale of the \( cc \) creation process, the time ordering of the gluon exchanges implied by Fig. 4a ceases to dominate higher twist contributions such as that of Fig. 4b [50], which are related to intrinsic charm [48]. There are in fact reasons to expect that the latter diagrams give a dominant contribution to charmonium production near threshold. First, there are many more such diagrams. Second, they allow the final state proton to have a small transverse momentum (the gluons need \( p_{\perp} \approx m_c \) to couple effectively to the \( cc \) pair, yet the overall transfer can still be small in Fig. 4b). Third, with several gluons coupling to the charm quark pair its quantum numbers can match those of a given charmonium state without extra gluon emission.

The above discussion is generic, and does not indicate how close to threshold the new effects actually manifest themselves. While more quantitative model calculations certainly are called for, this question can only be settled by experiment. It will be desirable to measure both the cross section and polarization for several charmonium states, as well as for open charm. At present, there are only tantalizing indications for novel phenomena at charm threshold, namely:

- **Fast \( cc \) pairs in the nucleon.** The distribution of charm quarks in the nucleon, as measured by deep inelastic lepton scattering, appears [56] to be anomalously large at high \( x \), indicating a higher twist intrinsic charm component [48]. An analogous effect is suggested by the high \( x_F \) values observed in \( \pi N \to J/\psi + J/\psi + X \) [57]. A proton Fock state containing charm quarks with a large fraction of the momentum will enhance charm production close to threshold.

- **\( J/\psi \) polarization in \( \pi^- p \to J/\psi + X \) for \( x_F \to 1 \).** Only compact projectile (\( \pi \)) Fock states contribute in the limit where the \( J/\psi \) carries almost all of the projectile momentum [58]. It may then be expected that the helicity of the
$J/\psi$ equals the helicity of the projectile, *ie*, the $J/\psi$ should be longitudinally polarized. This effect is observed both in the above reaction $^{30}$ and in $\pi N \rightarrow \mu^+ \mu^- + X \ [59]$. 

- **Polarization in $pp \rightarrow pp$ large angle scattering.** There is a sudden change in the $A_{NN}$ polarization parameter close to charm threshold for $90^\circ$ scattering $^{60}$. It has been suggested that this is due to an intermediate state containing a $c\bar{c}$ pair, which has low angular momentum due to the small relative momenta of its constituents $^{61}$. This idea could be tested at ELFE by investigating correlations between polarization effects in large angle compton scattering, $\gamma p \rightarrow \gamma p$, and charm production ($\gamma p \rightarrow c\bar{c}p$) near threshold.

- **Change in color transparency at charm threshold.** Intermediate states with a charm quark pair could also give rise to the sudden decrease in color transparency observed in $pA \rightarrow pp(A-1)$ close to charm threshold $^{62}$. Due to the low momentum of the constituents they expand to a large transverse size within the nucleus, thus destroying transparency $^{61}$. Again, $\gamma A$ reactions could provide important tests at ELFE.

### 3.2 Subthreshold Production

The high luminosities at ELFE will allow detailed studies of subthreshold production of charm(onium). It is well established that antiprotons and kaons are produced on nuclear targets at substantially lower energies than is kinematically possible on free nucleons $^{63}$. Thus the minimal projectile energy required for the process $pp \rightarrow \bar{p} + X$ on free protons at rest is $6.6$ GeV, while the kinematic limit for $pA \rightarrow \bar{p} + X$ on a heavy nucleus at rest is only $3m_N \simeq 2.8$ GeV. Antiproton production has been observed in $p + ^{63}$Cu collisions down to $E_{lab} \simeq 3$ GeV, very close to kinematic threshold. Scattering on a single nucleon in the nucleus would at this energy require a fermi momentum of $O(800)$ MeV. While the $pA$ data can be fit assuming such high Fermi momenta, this assumption leads to an underestimate of subthreshold production in $AA$ collisions by about three orders of magnitude $^{64}$.

There are at least two qualitatively different scenarios for the observed subthreshold production of antiprotons. Either (Fig. 5a) the projectile strikes a local ‘hot spot’ with a high energy density in the nucleus. The effective mass of the scatterer is high, lowering the kinematic threshold. Alternatively (Fig. 5b) the momentum required to create the antiproton is not transferred locally, but picked up in an extended longitudinal region: the nucleus forms a ‘femtoaccelerator’. Establishing either scenario would teach us something qualitatively new about rare, highly excited modes of the nucleus.

Real and virtual photoproduction of charm below threshold would be of crucial help in distinguishing the correct reaction mechanism, for several reasons.
The photon is pointlike, and is thus a clean probe of target substructure. In particular, effects due to the shrinking effective size of a hadron probe near threshold (*cf.* discussion above) are eliminated.

- The $c\bar{c}$ pair is created locally, within a proper time $\tau \simeq 1/m_c$. The extended acceleration scenario of Fig. 5b is thus not effective for charm production. If significant subthreshold charm production occurs (beyond what can be ascribed to standard fermi motion) this selects the hot spot scenario of Fig. 5a.

- Subthreshold production can be studied as a function of the virtuality $Q^2$ of the photon. Little $Q^2$ dependence is expected for $Q^2 \lesssim m_c^2$, due to the local nature of charm production. Nuclear hot spots smaller than $1/m_c$ would be selected at higher values of $Q^2$.

### 3.3 Interactions of $c\bar{c}$ Pairs in Nuclei

Close to threshold for the process $\gamma p \to J/\psi p$ on stationary protons the energy of the $J/\psi$ is $E_{J/\psi}^{lab} \simeq 7$ GeV. This corresponds to a moderate lorentz $\gamma$-factor $E_{J/\psi}/M_{J/\psi} \simeq 2.3$. Hence a significant expansion of the $c\bar{c}$ pair occurs inside large nuclei, and effects of charmonium bound states in nuclei may be explored.

Compared to the propagation of light quarks in nuclei, charm has the advantage that one can readily distinguish hidden (charmonium) from open ($DD$) charm
production. Thus the dependence of the $\sigma(J/\psi)/\sigma(D)$ ratio on the target size $A$ and on projectile energy indicates the amount of rescattering in the nucleus. The presently available data on the $A$-dependence of charmonium production is at much higher energies (cf section 2.5), and thus measures the nuclear interactions of a compact $c\bar{c}$ pair rather than of full-sized charmonium. Further information about the significance of the radius of the charmonium state can be obtained by comparing $\psi'$ to $J/\psi$ production on various nuclei. In high energy $hA$ and $\gamma A$ scattering both states have very similar $A$-dependence [46].

Information about the propagation of charmonium in nuclei is very important also for relativistic heavy ion collisions, where charmonium production may be a signal for quark-gluon plasma formation [4]. Precise information from ELFE would allow a more reliable determination of the background signal from charmonium propagation in ordinary nuclear matter.

Even though the $c\bar{c}$ pair is created with rather high momentum even at threshold, it may be possible to observe reactions where the pair is captured by the target nucleus, forming ‘nuclear-bound quarkonium’ [35]. This process should be enhanced in subthreshold reactions. There is no Pauli blocking for charm quarks in nuclei, and it has been estimated there is a large attractive van der waals potential binding the pair to the nucleus [36]. The discovery of such qualitatively new bound states of matter would be a scoop for any accelerator.

4. Summary

Charmonium production provides a valuable window to color dynamics. The experimental signal from the $J/\psi$ dilepton decay mode is very clean, allowing the measurement of a small signal in the presence of much more abundant background processes. The charmonium production process is hard due to the large mass of the charm quark. The binding energy is low, however, making charmonium a sensitive probe a color exchange processes.

Charmonium photoproduction was measured close to threshold soon after the discovery of the $J/\psi$ [8, 9]. The more recent experiments have all been done well above threshold, and have revealed a number of puzzles, including ‘anomalous’ production rates, polarization and nuclear target $A$-dependence.

The Color Evaporation Model [11] assumes that charmonium cross sections are universal fractions of $c\bar{c}$ production. It successfully describes the $E_{CM}$, $x_F$ and $p_\perp$ dependence of $J/\psi$ production, and in particular correctly predicts the relative magnitude of the Tevatron high $p_\perp$ data and the low $p_\perp$ data of fixed target experiments. The universality seems to be broken, however, in $\chi_c$ photoproduction and for scattering on nuclear targets.

The Color Singlet Model [23] successfully predicts (within the typically rather large uncertainties of charm production) the absolute normalization for $J/\psi$ pho-
toproduction and $\chi_{c2}$ hadroproduction. The model fails by more than an order of magnitude in $J/\psi$ and $\chi_{c1}$ hadroproduction, however.

The Color Octet Model [35] is based on a systematic NRQCD expansion in the relative velocity $v/c$ of the heavy quarks. The higher order terms in $v/c$ involve new non-perturbative parameters, which can be determined from a fit to the Tevatron $J/\psi$ data at high $p_{\perp}$. A fully consistent picture has yet to emerge. In particular, this approach overestimates $J/\psi$ photoproduction, underestimates $\Upsilon(3S)$ production and fails to describe the fixed target data on $J/\psi$ polarization.

ELFE will provide precise data on charmonium production close to threshold. New effects arise since only compact Fock states of the target can contribute to near-threshold production. Analogous effects have been observed at high energies through a change in the polarization state of the $J/\psi$ for $x_F \rightarrow 1$.

In scattering on nuclei, subthreshold charmonium production will be sensitive to nuclear ‘hot spots’, compact subclusters of high energy density. Such clusters could give rise to the observed high rates of subthreshold $\bar{p}$ and $K$ production [38], but light hadrons need not necessarily be created locally in the nucleus.

The relatively low momenta of the $c\bar{c}$ pairs produced close to threshold will allow studies of charmonium (rather than of compact $c\bar{c}$) interactions in the nucleus. Such interactions may explain the anomalous effects observed in the polarization and color transparency of large angle $pp$ elastic scattering. It may even be possible to study $c\bar{c}$ pairs at rest in nuclear matter, where they could form a new form of matter, nuclear bound quarkonium.

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