Determining Color-Octet $\psi$-Production Matrix Elements from $\gamma p$ and $ep$ Processes

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We calculated, within the NRQCD factorization formalism, the leading color-octet contributions to $\psi$ production in photon-nucleon and electron-nucleon collisions. The expressions obtained depend on the NRQCD matrix elements $\langle O^8_n(1S_0) \rangle$ and $\langle O^8_n(3P_J) \rangle$. These matrix elements can be determined by fitting to experimental data. The color-octet contribution to $\psi$ photoproduction is in the forward region of phase space, where there may be large corrections to the NRQCD result from higher twist terms. As to $\psi$ leptoproduction we point out that the theoretical uncertainties plaguing the photoproduction calculation vanish in the large momentum transfer limit. In this region of phase space the NRQCD formalism should be valid, making $\psi$ leptoproduction an ideal laboratory for testing the theory.

1. Introduction

The nonrelativistic QCD (NRQCD) factorization formalism developed by Bodwin, Braaten, and Lepage provides a rigorous theoretical framework within which quarkonium production can be studied. A central result of this formalism is that the cross section for the inclusive production of a quarkonium state $H$ is a sum of products having the form

$$\sigma(A + B \to H + X) = \sum_n \frac{F_n}{m_Q^{d_n-4}} \langle O^H_n \rangle,$$

where $m_Q$ is the mass of the heavy quark $Q$, $F_n$ are short-distance coefficients, and $O^H_n$ are NRQCD four-fermion production operators with naive energy dimension $d_n$. The short-distance coefficients, $F_n$, are associated with the production of a $Q\bar{Q}$ pair with quantum numbers indexed by $n$ (angular momentum $2S+1L_J$ and color 1 or 8). They can be calculated using perturbative techniques. The NRQCD production matrix elements, $\langle O^H_n \rangle \equiv \langle 0|O^H_n|0 \rangle$, parameterize the hadronization into $H$ of a $Q\bar{Q}$ pair with quantum numbers indexed by $n$. They can be determined phenomenologically.

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The power of the NRQCD formalism stems from the fact that Eq. (1) is essentially an expansion in the small parameter \( v^2 \), where \( v \) is the average relative velocity of the \( Q \) and \( \bar{Q} \) in the bound state \( H \). \( v^2 \sim 0.3 \) for charmonium. NRQCD \( v \)-scaling rules allow one to estimate the relative sizes of the various \( \langle O_n^H \rangle \). This information, along with knowledge of the dependence of the \( F_n \) on coupling constants, permits one to decide which terms must be retained in expressions for observables to reach a given level of accuracy. Generally, to leading order, factorization formulas involve only a few matrix elements, so several observables can be related by a small number of parameters. Thus it is possible to test the NRQCD factorization formalism by determining if a body of data can be consistently fit by the most important NRQCD production matrix elements. Moreover, by studying the regime in which the NRQCD factorization formalism fails we can gain valuable insight into the limitations of the theory.

As to \( J/\psi \) production, in many instances the most important NRQCD matrix elements are \( \langle O_8^\psi(1S_0) \rangle \), \( \langle O_8^\psi(3P_0) \rangle \), and \( \langle O_8^\psi(3P_J) \rangle \). These matrix elements appear in the expressions of rates for \( \psi \) production in hadronic collisions, in \( Z^0 \) decay, in \( e^+e^- \) annihilation, in photon-nucleon collisions, and in lepton-nucleon collisions. Fitting the leading order predictions to the various experimental data has revealed some inconsistencies. In particular the value determined for the linear combination \( \langle O_8^\psi(1S_0) \rangle + 3\langle O_8^\psi(3P_0) \rangle/m_c^2 \) at CDF appears to be incompatible with the value determined for the linear combination \( \langle O_8^\psi(1S_0) \rangle + 7\langle O_8^\psi(3P_0) \rangle/m_c^2 \) from photoproduction and other hadroproduction experiments. Another aspect of this problem is that if one uses the CDF measurement to make an estimate of the magnitude of \( \langle O_8^\psi(1S_0) \rangle \) and \( \langle O_8^\psi(3P_J) \rangle \), assuming both matrix elements to be positive, the color-octet contribution to inelastic \( \psi \) photoproduction is too large. Throughout the paper we will refer to this inconsistency as the “photoproduction conundrum”.

In this work we focus on aspects of \( \psi \) photoproduction and electroproduction. Within the context of these processes we investigate some of the issues involved in applying the NRQCD factorization formalism, and study the possible limitations of the theory. More precisely our goal is to see if an analysis of \( \psi \) leptoproduction can resolve the photoproduction conundrum.

The paper is divided into two parts. The first part, section 2, is a calculation of the forward \( \psi \) photoproduction rate. We fit the theoretical expression for the rate to experimental data and determine a value for the linear combination \( \langle O_8^\psi(1S_0) \rangle + 7\langle O_8^\psi(3P_J) \rangle/m_c^2 \). We point out that there are large corrections to this result; a sign that this process is not amenable to analysis within the NRQCD formalism.

In the second part of the paper, section 3, we present a calculation of the \( \psi \) leptoproduction rate. For large momentum-transfer squared, \( Q^2 \), this process does not suffer the sizable corrections afflicting the photoproduction calculation, and is, therefore, well within the regime of applicability of the NRQCD formalism. Unfortunately, at this time, there is no data available on forward \( \psi \) leptoproduction at large \( Q^2 \). Thus we fit the theoretical result to experimental data covering low to
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... moderate values of $Q^2$, and measure $\langle O_S^{\psi} (^1S_0) \rangle$ and $\langle O_S^{\psi} (^3P_0) \rangle$. We find a negative value for $\langle O_S^{\psi} (^3P_0) \rangle$. By studying the renormalization of the $P$-wave operator we argue that this is not shocking. The values of the color-octet matrix elements determined here resolve one aspect of the photoproduction conundrum: the CDF analysis is now consistent with photoproduction and other hadroproduction analyses. It is unclear, however, whether the other aspect of the photoproduction conundrum is resolved: that the color-octet contribution to inelastic $\psi$ photoproduction is too large.

2. Photoproduction of $\psi$

One of the earliest calculations of $\psi$ production was carried out by Berger and Jones in 1981. In this paper the authors present a calculation of the rate for $\psi$ production in $\gamma$-nucleon collisions carried out within the color-singlet model. In this model one assumes that there is a nonzero probability for a $Q\bar{Q}$ pair to form a hadron $H$ only if the $Q\bar{Q}$ pair is produced at short-distances (i.e. at distances on the order of $1/m_Q$ or less) with the quantum numbers of the dominant Fock state of $H$. For example a $c\bar{c}$ pair has a nonzero probability of forming a $\psi$ only if the $c\bar{c}$ pair is produced at short-distances in a color-singlet state with angular-momentum quantum numbers $^3S_1$.

In order to gain a deeper understanding of the color-singlet results we need to define the parameter $z \equiv N \cdot P/N \cdot k$. Here $N$ is the initial-state nucleon four-momentum, $k$ is the initial-state photon four-momentum, and $P$ is the $\psi$ four-momentum. In the rest frame of the nucleon $z$ is the fraction of the photon energy that is carried away by the $\psi$. The region of phase space where $z < 0.9$ is, by convention, defined as “inelastic”. The remaining region of phase space $0.9 < z < 1.0$ is defined as “forward”.

If one includes next-to-leading order QCD corrections and next-to-leading order relativistic corrections the color-singlet model explains the experimental data in the inelastic region. However, the color-singlet model prediction falls nearly an order of magnitude below the data in the forward region. This is not unexpected since, as Berger and Jones pointed out over a decade ago, in the forward region of phase space the final state gluon couples to on-shell quark lines; thus $\alpha_s$ for the vertex is ill-defined and the emission of the gluon is nonperturbative.

The failure of the color-singlet model to explain forward $\psi$ photoproduction leads us to the question: can $\psi$ photoproduction be understood in the NRQCD factorization formalism?

According to the NRQCD factorization formalism the photoproduction cross section is given by Eq. The $v$-scaling rules tell us that the probability for producing $H$ from a $Q\bar{Q}$ pair that does not have the quantum numbers of the dominant Fock state of $H$ is down by powers of $v^2$ relative to the probability for producing $H$ from a $Q\bar{Q}$ pair with the quantum numbers of the dominant Fock state of $H$. As pointed out previously, $v^2$ is not in general zero so it is possible for a $Q\bar{Q}$ pair produced at short-distances with any quantum numbers to hadronize into $H$. Only
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Fig. 1. Leading order diagrams for the photoproduction of a $c\bar{c}$ in a color-singlet, $^3S_1$ state.

Fig. 2. Leading order diagrams for the photoproduction of a $c\bar{c}$ in a color-octet state with angular momentum configuration $^1S_0$, $^3P_0$, and $^3P_2$.

in the $v \to 0$ limit is the color-singlet model recovered.

Within the NRQCD factorization formalism the leading contributions to the photoproduction cross section come from the production of a $c\bar{c}$ pair in a color-singlet $^3S_1$ state, or from the production of a $c\bar{c}$ pair in a color-octet state in either a $^1S_0$ or $^3P_J$ configuration. To leading order in $\alpha_s$ the color-singlet short-distance coefficient $F_1(^3S_1)$ can be determined from the diagrams in figure 1. The result is proportional to the expression derived for the $\psi$ photoproduction cross section in the color-singlet model. To leading order in $\alpha_s$ the color-octet short-distance coefficients $F_8(^1S_0)$ and $F_8(^3P_J)$ can be determined from the Feynman diagrams in figure 2. The color-octet matrix elements are suppressed by $v^4 \approx 0.1$ relative to the color-singlet matrix element, but the color-octet short-distance coefficients are enhanced by a $\pi/\alpha_s(2m_c) \approx 10$ relative to the color-singlet short-distance coefficient. Thus both contributions are equally important.

The NRQCD factorization formalism separates effects of short-distance scales of order $m_c$ or higher, which are associated with the production of the $c\bar{c}$, from long-distance scales such as $m_c v$, which are associated with the hadronization of the $c\bar{c}$ into the $\psi$. This separation is embodied in the factored form of the production cross section as shown in Eq. (1). The spirit of the formalism is that $\gamma + g \to c\bar{c}_1(^3S_1) + g$ is the correct short-distance process as long as the emission of the final state gluon takes place within a distance of order $1/m_c$ of the interaction point. This means that this gluon must have momentum of order $m_c$ or greater. If the final state gluon has momentum less than $m_c$ its emission is not part of the short-distance process and the diagrams shown in figure 1 do not describe the hard scattering.

Therefore, we hypothesize that the color-singlet calculation is not valid for the region of phase space $0.9 < z < 1.0$, since in this region the emission of the final
state gluon is nonperturbative, and is thus not part of the short distance process. Rather photoproduction in the forward region is described by the leading color-octet process. Inspired by the NRQCD formalism we will limit the color-singlet contribution to the region of phase space where \( 0 < z < 1 - \Lambda \), where \( \Lambda \) is some arbitrary cutoff of order \( v^2 \). Then the color-octet contribution produces \( \psi \) in the region \( 1 - \Lambda < z < 1 \). By convention in experiments the cutoff point between inelastic and forward \( \psi \) production is chosen to be \( z \approx 0.9 \). Thus we choose \( \Lambda \approx 0.1 \). We wish to emphasize the cutoff does not arise naturally in the NRQCD formalism, rather it is an assumption made in the spirit of the formalism.

The color-singlet contribution to \( \psi \) photoproduction has been studied extensively \(^{11}\). Let us now consider the color-octet contribution.

The leading color-octet contribution to the \( \psi \) photoproduction cross section can be calculated from the Feynman diagrams given in figure 2. The resulting expression is

\[
\sigma(\gamma + N \rightarrow \psi + X) = \int dx \, f_{g/N}(x) \, \frac{\alpha_s(2m_c)\alpha e^2\pi^3}{m_c^2} \, \delta(xs - 4m_c^2) \, \Theta, \tag{2}
\]

where \( x \) is the momentum fraction of the incoming gluon relative to the nucleon, \( f_{g/N}(x) \) is the gluon distribution function for the nucleon, and

\[
\Theta = \langle O_8^{\psi}(1S_0) \rangle + \frac{7}{m_c^2} \langle O_8^{\psi}(3P_0) \rangle. \tag{3}
\]

Since the values of the color-octet matrix elements are not known we can not make a prediction for the forward photoproduction cross section. However, we can fit the results to experimental data and make a prediction for \( \psi \) production in some other process.

Figure 3 shows a fit of Eq. (2) to forward cross-section measurements from the fixed target experiments E687 \(^{12}\), NA14 \(^{13}\), E401 \(^{14}\), NMC \(^{15}\), and E516 \(^{16}\). Using \( \alpha_s(2m_c) = 0.26 \) and \( m_c = 1.5 \) GeV we obtain the value

\[
\Theta = 0.02 \text{ GeV}^3, \tag{4}
\]

No theoretical error has been quoted here. The expression given in Eq. (2) is very sensitive to the value we choose for the parameter \( m_c \), which results in a large uncertainty in the value determined for \( \Theta \). Given this error, the number presented in Eq. (4) is consistent with the value \( \Theta = 0.03 \) GeV\(^3 \) measured in \( \pi N \) collisions \(^{17}\).

There is an important point to make regarding the calculation of forward \( \psi \) photoproduction. Namely, in the derivation of the factorization formula presented in Eq (1) higher twist terms have been neglected. In the forward region these higher twist terms can be large \(^{18}\). For example, they could describe correlations between the initial and final state resulting in diffractive and elastic processes. Such processes can have large contributions to the \( \psi \) forward photoproduction cross section, and can, therefore, significantly affect the value determined for \( \Theta \).
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\[ \sigma(\gamma p \rightarrow J/\psi X) \]

Given the large theoretical uncertainty associated with the forward photoproduction calculation it is best to regard the value presented in Eq. (4) as an upper limit. In fact, if the value determined for \( \Theta \) in photoproduction is consistent with fits of the color-octet matrix elements to other \( \psi \) production data we can be certain that higher twist corrections, and diffractive and elastic contributions are small.

3. Leptoproduction of \( \psi \)

Many of the theoretical uncertainties plaguing the photoproduction calculation can be avoided by requiring the incoming photon to be highly virtual. This introduces a new scale into the process: \( Q^2 \) the momentum transferred through the photon squared. Higher twist terms will be suppressed by powers of \( Q^2 \), and will, therefore, vanish in the large \( Q^2 \) limit.

A process in which the photon can be highly virtual is \( \psi \) leptoproduction. The calculation of \( \psi \) leptoproduction is analogous to the photoproduction calculation, except the incoming photon is off shell. In the region of phase space where \( 0.9 < z^* < 1.0 \) (the * denotes that the photon is virtual) the leading contribution comes from the fusion of the virtual photon and the gluon into a color-octet \( c\bar{c} \) pair in either a \( ^1S_0, ^3P_0, \) or \( ^3P_2 \) configuration, followed by the hadronization of the \( c\bar{c} \) pair into a \( \psi \). The Feynman diagrams used to determine the short-distance coefficients are shown in figure 4.

The expression for the cross section determined from the diagrams in figure 4 is

\[ \sigma(e + p \rightarrow e + \psi + X) = \int \frac{dQ^2}{Q^2} \int \frac{dy}{y} \int dx f_{g/N}(x) \delta(xys - 4m_c^2 - Q^2) \]
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Fig. 4. A two parameter fit to EMC data of the NRQCD factorization formalism result for forward leptoproduction of $\psi$.

\[ \frac{2\alpha_s(\mu^2)\alpha_s^2 c^2\pi^2}{xsm_c} \left\{ \frac{1 + (1 - y)^2}{y} \left[ \langle O_8^\psi(1S_0) \rangle + \frac{3Q^2 + 7(2m_c)^2}{xys} \langle O_8^\psi(3P_J) \rangle \right] \right\} \]

\[ - \frac{8(2m_c)^2 Q^2}{x^2 y^2 s} \frac{\langle O_8^\psi(3P_J) \rangle}{m_c^2} \]

(5)

where $\mu^2 = Q^2 + m_c^2$, and $x$ and $f_{g/N}(x)$ are the same as in Eq. (2). The momentum fraction of the virtual photon relative to the incoming lepton is $y \sim N \cdot q/N \cdot k$, where $N$ is the nucleon four-momentum, $q$ is the photon four momentum, and $k$ is the incoming lepton four-momentum.

The result presented in Eq (5) holds for all values of $Q^2$. Taking the limit $Q^2 \to 0$ one recovers the photoproduction result convoluted with the electron splitting function:

\[ \lim_{Q^2 \to 0} \sigma(e + P \to e + \psi + X) \to \frac{\alpha}{2\pi} \int dQ^2 \int_0^1 dy \frac{1 + (1 - y)^2}{y} \sigma(\gamma P \to \psi). \]

(6)

As discussed previously, in this limit corrections to the cross section from higher twist terms, may be large. However, in the high-energy limit $Q^2, s \gg (2m_c)^2$ we expect contributions from higher twist terms to vanish. Letting $Q^2, s \gg (2m_c)^2$ we obtain

\[ \lim_{m_c^2/Q^2, m_s^2/s \to 0} \sigma(e + P \to e + \psi + X) \to \frac{\alpha}{2\pi} \int dQ^2 \int dy \frac{1 + (1 - y)^2}{y} \]

\[ \int dx f_{g/N}(x) \frac{4\alpha_s(Q^2)\alpha_s^2 c^2\pi^3}{Q^2} \left( \langle O_8^\psi(1S_0) \rangle + \frac{3\langle O_8^\psi(3P_J) \rangle}{m_c^2} \right) \delta(xys - Q^2). \]

(7)

Note that this expression does not depend very strongly on the value chosen for $m_c$. Since theoretical corrections to Eq. (7) are expected to be small, high energy leptoproduction provides an excellent means to measure the linear combination $\langle O_8^\psi(1S_0) \rangle + 3\langle O_8^\psi(3P_J) \rangle/m_c^2$. This is precisely the linear combination of NRQCD matrix elements determined from CDF data on $\psi$ production at high transverse momentum. Therefore, $\psi$ leptoproduction data taken in the high energy limit will provide us with the opportunity to test the NRQCD factorization formalism by measuring the same linear combination of matrix elements in two different processes.

As of yet there is no $\psi$ leptoproduction data that truly falls in the high energy regime. Therefore we will naively fit Eq. (5) to the available data. The result of
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Fig. 5. A two parameter fit to EMC data of the NRQCD factorization formalism result for forward leptoproduction of $\psi$. The horizontal axis is $Q^2$, and the vertical axis is $d\sigma(\gamma^* + P \rightarrow \psi + X)/d\log Q^2$.

a fit to EMC data over the entire range of $Q^2$ ($0 < Q^2 < 15$ Gev$^2$) is shown in figure 5. The values of the color-octet matrix elements determined from this fit are:

$$
\langle O_{8}^{\psi}(1S_0) \rangle = 0.04 \text{ GeV}^3,
$$

$$
\frac{\langle O_{8}^{\psi}(3P_J) \rangle}{m_c^2} = -0.003 \text{ GeV}^3.
$$

Note that $\langle O_{8}^{\psi}(3P_J) \rangle$ is negative! Does this mean that the NRQCD factorization formalism fails to describe $\psi$ leptoproduction? Perhaps; remember there could be large corrections to the low $Q^2$ region. However, there is another explanation.

Loop corrections to NRQCD operators give rise to ultraviolet power divergences which have the form of renormalization of lower-dimensional operators. Since dimension six is the lowest possible energy dimension of NRQCD production operators the dimension-six operator $O_{8}^{\psi}(1S_0)$ will not have a power-divergent contribution. However, the dimension-eight operator $O_{8}^{\psi}(3P_J)$, will have power divergences proportional to dimension six operators. At order $\alpha_s$, using a momentum cutoff $\Lambda$, these divergences can be removed by defining the renormalized operator to be

$$
O_{8}^{\psi}(3P_J)_R = O_{8}^{\psi}(3P_J)_0 - c_1 \alpha_s \Lambda^2 O_1^{\psi}(3S_1) - c_8 \alpha_s \Lambda^2 O_{8}^{\psi}(3S_1),
$$

where the coefficients $c_1$ and $c_8$ are adjusted to cancel quadratic divergences at order $\alpha_s$. Matrix elements of the bare operator $O_{8}^{\psi}(3P_J)_0$ must indeed be positive definite, but this is not necessarily true for the renormalized operator. If one defines the operator $O_{8}^{\psi}(3P_J)$ using a method like dimensional regularization which automatically removes power divergences, the regularization method makes the above subtractions implicitly. Therefore the renormalized operator need not have positive matrix elements.
In particular, it is easy to see that the most important subtracted term in Eq. (9) is the one proportional to the matrix element $O^\psi_1(3S_1)$. This term is suppressed by a factor of $\alpha_s$, but it is enhanced by a quadratic divergence and a relative factor of $1/v^4$. Thus it is not too shocking if the resulting renormalized matrix element turns out to be negative. Note that renormalization respects the $v$-scaling rules which require the magnitude of the matrix element of $O^\psi_8(3P_J)$ to scale as $v^7$.

Accepting the explanation proffered above, let us compare the results presented in Eq. (8) to photoproduction and hadroproduction results. The numbers determined in leptoproduction are consistent with the photoproduction result given in Eq. (4), and are, therefore, consistent with the result of an analysis of $\pi N$ collisions. Using CDF data on $\psi$ production at the Tevatron, Cho and Leibovich have determined

$$\langle O^\psi_8(1S_0) \rangle + 3 \frac{\langle O^\psi_8(3P_J) \rangle}{m^2} = 0.066 \text{ GeV}^3$$

Substituting the values given in Eq. (8) into the left-hand side of Eq. (10) we obtain 0.03 GeV$^3$. Given the large theoretical uncertainty associated with calculations of $\psi$ production in hadronic collisions, these results are consistent.

4. Conclusion

We have calculated, within the NRQCD factorization formalism, the leading color-octet contributions to $\psi$ photoproduction and $\psi$ leptoproduction. The expressions obtained depend on the color-octet matrix elements $\langle O^\psi_8(1S_0) \rangle$ and $\langle O^\psi_8(3P_J) \rangle$. The NRQCD factorization formalism may be tested by fitting these matrix elements to experimental data, and then making predictions for $\psi$ production in some other process.

The color-octet contribution to the photoproduction cross section is in the region of phase space where the $\psi$ is produced in the forward direction. In this region higher twist terms, which were neglected in the derivation of the factorization formula Eq. (1), may be large. Therefore, forward $\psi$ photoproduction is not amenable to testing the NRQCD factorization formalism. However, we can learn about the limitations of the theory, and the size of possible corrections.

The leading color-octet contribution to the $\psi$ leptoproduction cross section does not suffer from the same problems as the photoproduction calculation if we restrict ourselves to the high $Q^2$ regime. In this region $\psi$ leptoproduction should provide an ideal laboratory for testing the NRQCD factorization formalism. However, there is at this time no experimental data for $\psi$ production in the asymptotic regime. Therefore, keeping in mind that there may be large corrections to the cross section in the low $Q^2$ region, we fit our results to EMC data for $0 < Q^2 < 15 \text{ GeV}^2$. We determine $\langle O^\psi_8(1S_0) \rangle = 0.04$, and $\langle O^\psi_8(3P_0) \rangle = -0.003$. The negative value for the $P$-wave matrix element is acceptable since the renormalized $P$-wave operator is a subtraction of two divergent terms, $O^\psi_8(3P_J)_T = O^\psi_8(3P_J)_0 - c_1 \alpha_s A^2 O^\psi_1(3S_1)$, where the second term on the right-hand-side is larger than the first term on the right-hand-side. The values determined for the color-octet matrix elements
resolve one aspect of the photoproduction conundrum: the discrepancy between the CDF analysis and photoproduction and other hadroproduction analysis. However it is not clear if the other aspect of the photoproduction conundrum is resolved: the color-octet contribution to inelastic $\psi$ production is too large.

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