The Leading Particle Effect from Heavy-Quark Recombination

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The leading particle effect in charm hadroproduction is an enhancement of the cross section for a charmed hadron D in the forward direction of the beam when the beam hadron has a valence parton in common with the D. The large D^+/D^- asymmetry observed by the E791 experiment is an example of this phenomenon. We show that the heavy-quark recombination mechanism provides an economical explanation for this effect. In particular, the D^+/D^- asymmetry can be fit reasonably well using a single parameter whose value is consistent with a recent determination from charm photoproduction.

Fixed-target hadroproduction experiments have observed large asymmetries in the production of charmed mesons and baryons [1–4]. These asymmetries are commonly known as the "leading particle effect", since charmed hadrons having a valence parton in common with the beam hadron are produced in greater numbers than other charmed hadrons in the forward region of the beam. For example, the E791 experiment [1], in which a 500 GeV $\pi^-(\overline{u}d)$ beam is incident on a nuclear target, observes a substantial excess of $D^-(\overline{c}d)$ over $D^+(c\overline{d})$ when the charmed mesons are produced with large momentum along the direction of the π^- beam. The asymmetry,

$$\alpha[D^+] = \frac{d\sigma[D^-] - d\sigma[D^+]}{d\sigma[D^-] + d\sigma[D^+]}\,, \tag{1}$$

is as large as ~ 0.7 for the most forward D mesons measured. Asymmetries in the production of charmed baryons have also been observed [2–4].

In contrast with the large experimental asymmetries, perturbative QCD predicts that the asymmetries should be very small. The QCD factorization theorem for heavy particle production [5] states that the cross section for producing a D meson in the collision of two hadrons can be written as

$$\begin{aligned} &d\sigma[hh' \to D + X] \\ &\quad = \sum_{i,j} f_{i/h} \otimes f_{j/h'} \otimes d\hat{\sigma}(ij \to c\overline{c} + X) \otimes D_{c\to D}\,, \end{aligned} \tag{2}$$

where $f_{i/h}$ is the distribution function for the parton i in the hadron h, $d\hat{\sigma}(ij \to c\overline{c}+X)$ is the parton cross section and $D_{c\to D}$ is the fragmentation function for a c quark hadronizing into a D meson. The corrections to Eq. (2) are suppressed by powers of $\Lambda_{\rm QCD}/m_c$ or $\Lambda_{\rm QCD}/p_\perp$. A study of $O(\Lambda_{\rm QCD}/m_c)$ corrections to charm production can be found in Ref. [6]. The leading order (LO) diagrams for $gg \to c\overline{c}$ and $q\overline{q} \to c\overline{c}$ produce c and $\overline{c}$ quarks symmetrically. The c and $\overline{c}$ fragment independently into D and $\overline{D}$ mesons, and charge conjugation invariance requires that $D_{c\to D} = D_{\overline{c}\to\overline{D}}$. Therefore, LO perturbative QCD predicts no asymmetry between D and $\overline{D}$ mesons. Asymmetries are generated at next-to-leading order (NLO) [7–10], but they are too small by an order of magnitude or more to account for the experimentally observed asymmetries.

Thus, charm asymmetries are interesting because they probe the power corrections to Eq. (2). Most attempts to explain the leading particle effect have employed phenomenological models of hadronization. One explanation is the "beam drag effect" [11] in which charm quarks hadronize into charmed mesons by the decay of a color string connected to partons in the beam remnant. Calculations of the beam drag effect employ the Lund string fragmentation model [12], as implemented in the PYTHIA Monte Carlo [13]. Predictions for the asymmetries are sensitive to the model for the beam remnant, as well as other parameters in PYTHIA. These models can be tuned to fit data if one uses a large charm quark mass and gives the partons intrinsic transverse momentum of $\sim 1\,$GeV [1]. Another class of models [14] are based on the possibility of intrinsic charm in the nucleon [15]. These models are sensitive to the poorly determined intrinsic charm structure function as well as the model of the beam remnant and predict smaller asymmetries than are experimentally observed.

In this letter we show that the leading particle effect can be explained quantitatively and economically by the heavy-quark recombination mechanism introduced in Ref. [16]. This mechanism has already been applied to charm asymmetries in fixed-target photoproduction experiments in Ref. [17], where it was shown that the charm asymmetries observed in the experiments E687 and E691 at Fermilab can be fit well with just one free parameter. Here we apply the heavy-quark recombination mechanism to the much larger asymmetries observed in the E791 hadroproduction experiment.

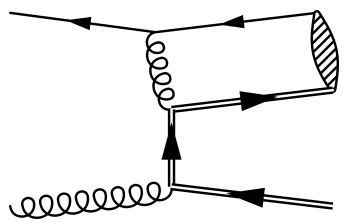

FIG. 1. Example of a diagram for $c\overline{q}$ recombination into a D meson. Single lines are light quarks, double lines are heavy quarks and the shaded blob is the D meson.

In the heavy-quark recombination mechanism, a heavy quark or antiquark recombines with a light parton that participates in the hard-scattering process rather than a spectator parton from the beam or target. A nonperturbative parameter that characterizes the probability for the light parton to bind to the heavy quark to form a meson sets the overall normalization of the cross section. Since the asymmetry is generated in the hard process, the dependence of the asymmetry on kinematic variables is calculable within perturbative QCD. Therefore, heavy-quark recombination provides a simpler and more predictive explanation for the asymmetries than conventional hadronization models.

An example of a Feynman diagram contributing to this process is depicted in Fig. 1. A light antiquark $\overline{q}$ participates in a hard-scattering process which produces a c and $\overline{c}$. The outgoing $\overline{q}$ emerges from the hard-scattering process with momentum that is soft in the rest frame of the outgoing c quark, and the c and $\overline{q}$ then bind to form a D meson. There is an analogous process in which a light quark combines with a $\overline{c}$ to form a $\overline{D}$ meson. We emphasize that heavy-quark recombination is not taken into account by higher order perturbative QCD corrections to the fragmentation contribution. The NLO correction includes a parton subprocess $\overline{q}g \to \overline{q}c\overline{c}$ that is similar to the parton subprocess of the diagram in Fig. 1. However, for most of the phase space the outgoing $\overline{q}$ hadronizes into a jet that is distinct from the jets containing the c and $\overline{c}$. When the $\overline{q}$ has small momentum in the c rest frame, nonperturbative effects can bind the c and $\overline{q}$ and enhance the cross section. This enhancement, which is not present in the NLO perturbative calculation, is accounted for by heavy-quark recombination.

The heavy-quark recombination contribution to the D meson cross section is:

$$d\hat{\sigma}[D] = d\hat{\sigma}[\overline{q}g \to (c\overline{q})^n + \overline{c}]\, \rho[(c\overline{q})^n \to D]\,. \tag{3}$$

This cross section must be convolved with parton distributions for the $\overline{q}$ and g in the colliding hadrons. The symbol $(c\overline{q})^n$ indicates that the $\overline{q}$ has momentum $O(\Lambda_{\rm QCD})$ in the rest frame of the c and that the $(c\overline{q})^n$ has the color and angular momentum quantum numbers specified by n. $d\hat{\sigma}(\overline{q}g \to (c\overline{q})^n + \overline{c})$ is calculable in perturbative QCD, while $\rho[(c\overline{q})^n \to D]$ is a nonperturbative factor proportional to the probability for the $(c\overline{q})^n$ to evolve into a state including the D meson.

A detailed description of the calculation of $d\hat{\sigma}[\overline{q}g \to (c\overline{q})^n + \overline{c}]$ can be found in Ref. [16]. In this letter, we summarize the most important features. In most regions of phase space, the heavy quark recombination contribution is power-suppressed relative to the fragmentation contribution in Eq. (2) in accord with the factorization theorems of QCD. Let θ be the angle between the incoming $\overline{q}$ and the outgoing D meson in the parton center-of-momentum frame. At $\theta = \pi/2$, the ratio of the parton cross sections for heavy-quark recombination and LO gluon-gluon fusion is

$$\left.\frac{d\hat{\sigma}[\overline{q}g \to (c\overline{q})(^1S_0^{(1)}) + \overline{c}]}{d\hat{\sigma}[gg \to \overline{c}c]}\right|_{\theta=\pi/2} \approx \frac{256\,\pi}{567}\alpha_s \frac{m_c^2}{p_\perp^2 + m_c^2},$$

$$\left.\frac{d\hat{\sigma}[\overline{q}g \to (c\overline{q})(^3S_1^{(1)}) + \overline{c}]}{d\hat{\sigma}[gg \to \overline{c}c]}\right|_{\theta=\pi/2} \approx \frac{256\,\pi}{189}\alpha_s \frac{m_c^2}{p_\perp^2 + m_c^2}.$$

Using the expected scaling $\rho \sim \Lambda_{\rm QCD}/m_c$, we find that heavy-quark recombination is an $O(\Lambda_{\rm QCD} m_c/p_\perp^2)$ power correction for $p_\perp \gg m_c$. However, the heavy-quark recombination cross section is strongly peaked when the D is produced in the forward region of the incoming $\overline{q}$. At $\theta = 0$, the ratio of the parton cross sections is

$$\left.\frac{d\hat{\sigma}[\overline{q}g \to (c\overline{q})(^1S_0^{(1)}, {}^3S_1^{(1)}) + \overline{c}]}{d\hat{\sigma}[gg \to \overline{c}c]}\right|_{\theta=0} \approx \frac{256\,\pi}{81}\alpha_s.$$

Thus, there is no kinematic suppression factor when the $(c\overline{q})^n$ is produced in the forward region of the incoming $\overline{q}$. Heavy-quark recombination provides a natural explanation for the leading particle effect because in the forward region, the cross section for a $D(\overline{D})$ meson carrying a $\overline{q}(q)$ that matches a valence parton in the beam is larger than that of other charmed mesons since valence quark structure functions are larger than sea quark structure functions.

If the $(c\overline{q})^n$ hadronizes into a D meson and nothing else, the $(c\overline{q})^n$ must be in a color-singlet state with the same flavor and angular momentum quantum numbers as the D. This contribution to $\rho[(c\overline{q})^n \to D]$ is proportional to the square of a moment of the D meson light-cone wavefunction and it scales as $\Lambda_{\rm QCD}/m_c$. However one should also allow for nonperturbative transitions in which the $(c\overline{q})^n$ hadronizes into states including additional soft hadrons in the rest frame of the D. The inclusive parameter $\rho[(c\overline{q})^n \to D]$, which includes these additional contributions, is still expected to scale like $\Lambda_{\rm QCD}/m_c$. Furthermore, the $(c\overline{q})^n$ can have different color and angular momentum quantum numbers than

the D meson in the final state. Since the momentum of the light quark is $O(\Lambda_{\rm QCD})$, amplitudes for production of $(c\overline{q})^n$ with $L > 0$ are suppressed relative to S-waves by powers of $\Lambda_{\rm QCD}/m_c$ or $\Lambda_{\rm QCD}/p_\perp$. The heavy-quark recombination contribution to D meson production thus contains four free parameters:

$$\rho_1^{\rm sm} = \rho[c\overline{d}(^1S_0^{(1)}) \to D^+], \rho_1^{\rm sf} = \rho[c\overline{d}(^3S_1^{(1)}) \to D^+], \quad (4)$$
$$\rho_8^{\rm sm} = \rho[c\overline{d}(^1S_0^{(8)}) \to D^+], \rho_8^{\rm sf} = \rho[c\overline{d}(^3S_1^{(8)}) \to D^+].$$

Here the superscript sm stands for spin-matched and sf stands for spin-flipped. (Nonperturbative transitions in which the light quark flavor of the $(c\overline{q})^n$ differs from that of the D are suppressed in the large N_c limit of QCD and will be ignored in this analysis.) Heavy-quark symmetry relates the four parameters appearing in the production of D^{*+} to the four parameters in Eq. (4). Parameters for D^- and D^0 production can be related using charge conjugation and isospin symmetry. The color-octet contributions are analogous to the color-octet production matrix elements that play a prominent role in the theory of quarkonium production [18]. If the $\overline{d}$ appearing in Eq. (4) were a heavy antiquark, the parameters $\rho_1^{\rm sf}, \rho_8^{\rm sm}$ and $\rho_8^{\rm sf}$ would be suppressed by powers of v, where v is the typical velocity of the antiquark in the bound state. However, the $\overline{d}$ is light, so $v \sim 1$ and there is no apparent suppression of these parameters.

In photoproduction, the $O(\alpha\,\alpha_s^2)$ color-octet and color-singlet heavy-quark recombination cross sections have the same functional form, so the cross section depends only on linear combinations of color-singlet and color-octet parameters of the form $\rho_1 + \rho_8/8$. The best fit to fixed-target photoproduction asymmetries in Ref. [17] yielded $\rho_1^{\rm sm} + \rho_8^{\rm sm}/8 = 0.15$. Including the $\rho^{\rm sf}$ parameters does not improve the fit unless $\rho_1^{\rm sf} + \rho_8^{\rm sf}/8$ is negative, which is unphysical. In the case of fixed target hadroproduction, the color-octet and color-singlet cross sections have different functional forms, so the asymmetries depend on all four parameters. However, we find that the asymmetries measured by the E791 experiment can be fit rather well by the single parameter $\rho_1^{\rm sm}$. In this analysis, we only include $\rho_1^{\rm sm}$ and set the other parameters to zero.

There are two contributions to the heavy-quark recombination cross section for a D meson:

$$a) \quad \sum_n d\hat{\sigma}[\overline{q}g \to (c\overline{q})^n + \overline{c}]\, \rho[(c\overline{q})^n \to D], \quad (5)$$
$$b) \quad \sum_{q,n} d\hat{\sigma}[qg \to (\overline{c}q)^n + c]\, \rho_n[(\overline{c}q)^n \to \overline{D}] \otimes D_{c\to D}.$$

In process $a)$, a light antiquark recombines with a c to form a D meson. In process $b)$, a $\overline{c}$ participates in the recombination process, and a D meson is produced via fragmentation from the c quark which does not recombine. For $D^\pm$ production, process $b)$ partially dilutes the asymmetry generated by $a)$. We take $m_c = 1.5\,$GeV

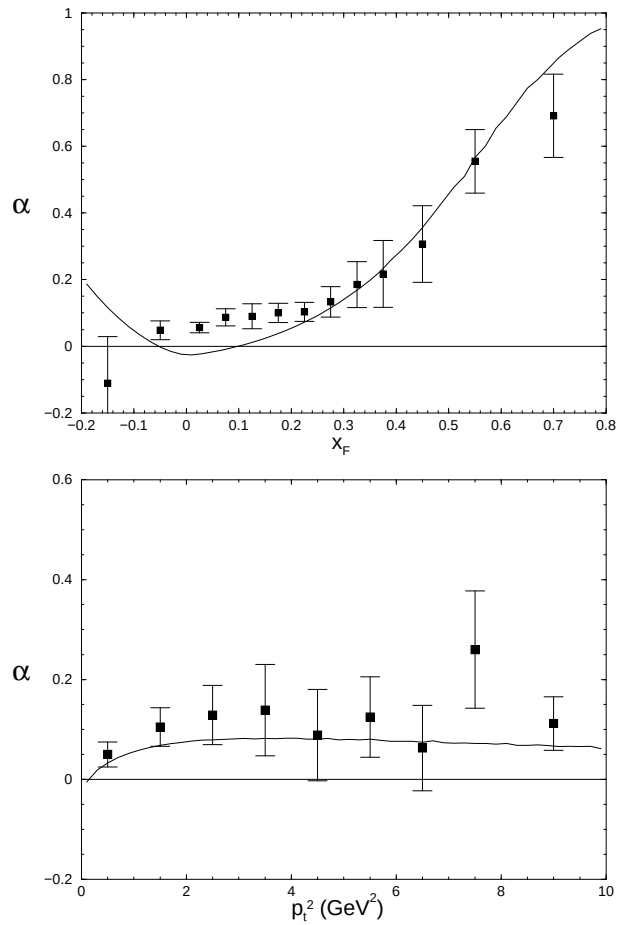

FIG. 2. The asymmetry variable $\alpha[D^+]$ vs. x_F and $p_\perp^2$. The data points are the measurements of E791 and the solid line is our prediction with $\rho_1^{\rm sm} = 0.06$.

and set the renormalization and factorization scales to be $\sqrt{p_\perp^2 + m_c^2}$. The parton distributions are GRV 98 LO [19] for the nucleon and GRV-P LO [20] for the pion. The E791 experiment uses a target consisting mostly of carbon, so the nucleon structure function is an isospin symmetric linear combination of proton and neutron. We use the one-loop expression for α_s with 4 active flavors and $\Lambda_{\rm QCD} = 200\,$MeV. We include only the LO fragmentation diagrams. If the NLO corrections are approximated by including a K factor, then $\rho_1^{\rm sm}$ should be multiplied by the same K factor to obtain the same asymmetry. We use the Petersen parametrization for $D_{c\to D}$ with $\epsilon = 0.06$ and the fragmentation probabilities are determined from data in Ref. [21]. Contributions to the D cross section from feeddown from D^* decay are included. Feeddown from other excited D meson states is expected to be small.

The predictions for $\alpha[D^+]$ as a function of x_F and $p_\perp^2$ are compared to the E791 data in Fig. 2. A least squares fit to all the data yields $\rho_1^{\rm sm} = 0.06$. The $p_\perp$ dependence is described very well by the heavy-quark recombination

mechanism. The x_F distribution is described well for $x_F > 0.2$, while our calculation underpredicts the asymmetry in the region $0.0 < x_F < 0.2$. It is possible to obtain a better fit to the asymmetry in this region if one allows nonvanishing values of $\rho_1^{\rm sf}$, $\rho_8^{\rm sm}$ and $\rho_8^{\rm sf}$. While we expect heavy-quark recombination to dominate in the forward region, other $O(\Lambda_{\rm QCD}/m_c)$ corrections to fragmentation may be important near $x_F = 0$ and could also account for the discrepancy. A systematic analysis of all $O(\Lambda_{\rm QCD}/m_c)$ corrections to D cross sections is needed to address this issue, but this is beyond the scope of this paper. Although α was not measured at large negative x_F, it must be positive in this region in accord with our prediction because of the leading particle effect associated with the target nucleons.

The value of $\rho_1^{\rm sm}$ extracted from the fits is consistent with the scaling $\rho_1^{\rm sm} \sim O(\Lambda_{\rm QCD}/m_c)$. A lower bound on $\rho_1^{\rm sm}$ can be obtained by assuming that $\rho_1^{\rm sm}[(c\overline{q})^n \to D]$ is saturated by a final state consisting of only the D. Then $\rho_1^{\rm sm}$ is proportional to the square of a moment of the D light-cone wavefunction which can be bounded using heavy-quark effective theory arguments [23]. This value is smaller than the lower bound $\rho_1^{\rm sm} = 0.15$ from photoproduction fits [17]. However, the uncertainty in this extraction due to higher order perturbative corrections and $O(\Lambda_{\rm QCD}/m_c)$ nonperturbative corrections could easily be a factor of 2. Furthermore, the fits in Ref. [17] used E687 data that was not corrected for efficiencies because of correlations between the measured asymmetries and the production model used in the Monte Carlo for simulating the trigger [24]. Given all these uncertainties, we regard the values of $\rho_1^{\rm sm}$ extracted from hadroproduction and photoproduction to be consistent.

It would be interesting to extend the analysis of this paper to asymmetries measured in experiments with different beams and for different charmed hadrons, particularly charmed baryons. Baryon asymmetries could be generated by a process similar to that of Fig. 1 with the light antiquark replaced by a light quark. There is an attractive force between the c and q when their color state is the $\overline{3}$ of $SU(3)$ that can enhance the cross section in this channel. It is natural to expect the $(cq)^n$ diquark to hadronize to a state with a charmed baryon. The SELEX collaboration has measured $\Lambda_c^\pm$ asymmetries in experiments with π^-, Σ^- and p beams [2]. The Λ_c^+ and Λ_c^- both have a valence quark that matches one of the valence quarks of the π^-, while only the Λ_c^+ has a valence quark in common with the p and Σ^-. Therefore, heavy-quark recombination predicts that $\Lambda_c^\pm$ asymmetries are much greater for p and Σ^- beams than for a π^- beam. This prediction is in agreement with SELEX measurements, which find $\alpha[\Lambda_c^-] \approx 1$ for p and Σ^- beams and $\alpha[\Lambda_c^-] \approx 0.2$ for π^- beams.

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