Charm production asymmetries from heavy-quark recombination

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Abstract. Charm asymmetries in fixed-target hadroproduction experiments are sensitive to power corrections to the QCD factorization theorem for heavy quark production. A power correction called heavy-quark recombination has recently been proposed to explain these asymmetries. In heavy-quark recombination, a light quark or antiquark participates in a hard scattering which produces a charm-anticharm quark pair. The light quark or antiquark emerges from the scattering with small momentum in the rest frame of the charm quark, and together they hadronize into a charm particle. The cross section for this process can be calculated within perturbative QCD up to an overall normalization. Heavy-quark recombination explains the observed $D$ meson and $\Lambda_c$ asymmetries with a minimal set of universal nonperturbative parameters.

In this talk I will discuss asymmetries in the production of charm particles in fixed-target hadroproduction experiments [1, 2, 3, 4, 5]. These asymmetries are much larger than predicted by perturbative QCD calculations, so they are a sensitive probe of nonperturbative aspects of heavy particle production. Asymmetries in the production of light particles such as pions and kaons have also been observed, but the production of particles containing heavy quarks is under better theoretical control. When the mass of the quark is heavier than $\Lambda_{QCD}$, as is the case for charm, perturbative QCD can be applied even when the particle is produced without large transverse momentum. In addition, nonperturbative effects can be organized in an expansion in $\Lambda_{QCD}/m_c$.

The differential cross-section for the production of a charm particle, $H$, in the collision of two hadrons, $A$ and $B$, is believed to factorize in the following manner [6]

$$d\sigma[A + B \rightarrow H + X] = \sum_{i,j} f_{i/A} \otimes f_{j/B} \otimes d\hat{\sigma}[ij \rightarrow c\bar{c} + X] \otimes D_{c\rightarrow H} + \ldots.$$  

Here $i,j$ denote partons, $f_{i/A}$ and $f_{j/B}$ are parton distribution functions, $D_{c\rightarrow H}$ is the fragmentation function for $c$ hadronizing into $H$ and $d\hat{\sigma}[ij \rightarrow c\bar{c} + X]$ is a perturbatively calculable short-distance cross section. The ellipsis represents corrections to the factorized form of the cross section that are suppressed by $\Lambda_{QCD}/m_c$, or possibly $\Lambda_{QCD}/p_\perp$ if $p_\perp \gg m_c$.

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The leading contribution to the factorization theorem in Eq. (1) predicts that charm particles and their antiparticles will be produced symmetrically. The leading order partonic processes, $gg \rightarrow c\overline{c}$ and $q\overline{q} \rightarrow c\overline{c}$, produce charm quarks and anticharm quarks with identical kinematic distributions. The fragmentation functions $D_{c \rightarrow H}$ and $D_{c \rightarrow \overline{H}}$ are identical due to the charge conjugation invariance of the strong interactions. No asymmetry between $H$ and $\overline{H}$ is generated at leading order in perturbation theory. Next-to-leading order perturbative corrections \cite{7, 8, 9, 10} can generate asymmetries but these are quite small. The asymmetry, defined by

$$
\alpha[H] = \frac{\sigma[H] - \sigma[\overline{H}]}{\sigma[H] + \sigma[\overline{H}]},
$$

(2)
is never larger than a few percent.

The asymmetries observed in experiments can be much larger \cite{1, 2, 3, 4, 5}. One well-known phenomenon is the “leading particle effect” in fixed-target hadroproduction. Charm hadrons sharing a valence parton with the beam hadron are produced in greater numbers in the forward direction of the beam than particles that do not share a valence quark with the beam. For instance, experiments with a $\pi^-$ beam incident on a nuclear target observe many more $D^-$ and $D^0$ than $D^+$ and $\overline{D}^0$ in the forward direction of the $\pi^-$ beam. $\alpha[D^-]$ rises from nearly zero in the central region, $x_F \approx 0$, to 0.7 at the highest $x_F$ measured. In the forward region of the $\pi^-$ beam almost six $D^-$ are produced for every $D^+$. Large asymmetries are also observed in charm baryon production. In $pN$ collisions $\alpha[\Lambda_c^+] \approx 1$ for all $x_F > 0.2$.

Smaller asymmetries are also observed even when there is no leading particle effect. Examples include fixed-target photoproduction \cite{11, 12, 13}, where the beam has no valence quark quantum numbers, the production of $D_s$ mesons in fixed-target hadroproduction experiments with $\pi$ or $p$ beams, and $\Lambda_c$ production in experiments with $\pi^-$ beams. In the last case, there is no asymmetry from the leading particle effect because the $\Lambda_c^+$ shares a $d$ quark with the $\pi^-$ while the $\Lambda_c^-$ shares a $\bar{u}$ with the $\pi^-$. These asymmetries are smaller than those observed when there is a leading particle effect but still larger than perturbative QCD predictions.

Traditionally the asymmetries have been explained by nonperturbative models of hadronization. A commonly used model is the Lung string fragmentation model \cite{14} which can be implemented using PYTHIA \cite{15}. (Another model of string fragmentation can be found in Ref. \cite{16}). The asymmetry is generated by the “beam drag effect” \cite{17} in which the charm quark binds to the remnants of the incident hadron via the formation of a color string. These models can be tuned to fit the data but this can require an unusually large charm quark mass and large intrinsic transverse momentum for the partons in the incoming hadrons \cite{1}. The PYTHIA Monte Carlo with default parameters rarely predicts the asymmetries correctly \cite{1} and in the case of $\Lambda_c$ asymmetries in $\pi N$ collisions \cite{4} gets the sign of the asymmetry wrong. Another approach is the recombination model first introduced in Ref. \cite{18} (for recent analyses using similar methods, see Refs. \cite{19, 20, 21}). In this model the charm quarks coalesce with spectator partons in the beam hadrons whose momentum distribution is determined by double
parton distributions. Finally there are models that rely on the existence of intrinsic charm in the incident hadron wavefunction to generate the asymmetry [22, 23, 24]. These models are sensitive to a number of poorly determined nonperturbative functions such as distributions of partons in the remnant and functions that parametrize recombination probabilities.

Since the asymmetries observed in nature are much larger than what is predicted by perturbative calculations, they are a direct probe of the power corrections to the QCD factorization theorem. Recent work has demonstrated that an $O(\Lambda_{QCD}/m_c)$ power correction called heavy-quark recombination provides a simple explanation of charm meson and baryon asymmetries in photo- and hadroproduction experiments [25, 26, 27, 28]. This approach differs from previous nonperturbative models in that the asymmetry is generated in the short-distance process so cross sections are calculable up to an overall normalization set by a few universal nonperturbative parameters. For $D$ mesons, the dominant contribution comes from a process in which a light antiquark participates in a hard scattering process that produces a charm-anticharm quark pair. The light antiquark emerges from the hard scattering with momentum of $O(\Lambda_{QCD})$ in the rest frame of the charm quark, then the light antiquark and charm quark hadronize into a final state that includes a $D$ meson. The process is depicted in Fig. 1. This $c\bar{c}$ recombination process gives a contribution to the $D$ meson cross section of the form

$$d\hat{\sigma}[\bar{q}g \rightarrow D + X] = \sum_n d\hat{\sigma}[\bar{q}g \rightarrow c\bar{c}(n) + \bar{c}] \rho[c\bar{c}(n) \rightarrow D].$$

(3)

In this formula, $d\hat{\sigma}[\bar{q}g \rightarrow c\bar{c}(n) + \bar{c}]$ is a short-distance cross section for producing a $c\bar{c}$ with quantum numbers denoted by $n$ and $\rho[c\bar{c}(n) \rightarrow D]$ parametrizes the hadronization of the $c\bar{c}$ into a state that includes a $D$ meson.

The NLO correction to the fragmentation cross section in Eq. (1) includes a subprocess $\bar{q}g \rightarrow \bar{q}c\bar{c}$ which is similar to the short-distance part of the mechanism depicted in Fig. 1. However, in the NLO calculation the $c$ and $\bar{q}$ hadronize
Figure 2. Example of a diagram for $c\bar{q}$ recombination, the leading mechanism for charm baryon production via heavy-quark recombination.

independently, so this correction does not account for the possibility that the $c\bar{q}$ can bind nonperturbatively and hadronize into the $D$. For this reason, the heavy-quark recombination mechanism is an $O(\Lambda_{\text{QCD}}/m_c)$ correction to Eq. (1) rather than part of the NLO correction to the fragmentation contribution.

Because the light antiquark is massless it is natural to expect the heavy-quark recombination contribution to be a convolution of a short-distance cross section with a distribution function that depends on the fraction of the light-cone momentum carried by the light quark. However, to lowest order in $\Lambda_{\text{QCD}}/m_c$ only the leading moment of such a distribution contributes. Because the cross section is inclusive, the final state may include other soft quanta besides the $D$ meson. Soft gluons emitted in the hadronization process can change the total angular momentum and color quantum numbers of the $c\bar{q}$ produced in the short-distance process. Therefore the color and angular momentum quantum numbers of the $c\bar{q}$ can be different from the $D$ meson. Amplitudes for production of $c\bar{q}$ in $L > 0$ partial waves are suppressed by additional powers of $\Lambda_{\text{QCD}}/m_c$ relative to S-waves and can be neglected. It is also possible for the light antiquark flavor quantum number of the $D$ to be different than that of the $c\bar{q}$ due to light quark-antiquark pair production in the hadronization process. However, light quark-antiquark pair production is suppressed in the large-$N_c$ limit of QCD so this effect is a subleading correction to $D$ meson production. This leaves four parameters for heavy-quark recombination into $D^+$ mesons:

$$\rho_1 = \rho[cd(1S_0^{(1)}) \to D^+], \quad \tilde{\rho}_1 = \rho[cd(3S_1^{(1)}) \to D^+],$$

$$\rho_8 = \rho[cd(1S_0^{(8)}) \to D^+], \quad \tilde{\rho}_8 = \rho[cd(3S_1^{(8)}) \to D^+].$$

These parameters scale with the heavy quark mass as $\Lambda_{\text{QCD}}/m_c$ and explicit expressions in terms of nonperturbative QCD matrix elements can be found in Ref. [29]. Analogous parameters for $D^0$ and $D^-$ mesons are obtained by using isospin symmetry and charge conjugation invariance, while parameters for $D^{*+}$ states are related to those in Eq. (4) by heavy-quark spin symmetry.
Charm production asymmetries from heavy-quark recombination

To form a baryon from $c\bar{q}$ recombination requires the production of at least two light quark-antiquark pairs which is suppressed by $1/N_c^2$, so $c\bar{q}$ recombination should contribute mostly to $D$ meson production. The process which gives the leading contribution to charm baryon production is $cq$ recombination which is shown in Fig. 2. This is the same as $c\bar{q}$ recombination except a light quark participates in the recombination process instead of a light antiquark. A light quark-antiquark pair must be produced for the $cq$ to hadronize into a state that has a charm baryon or charm meson, so there is a $1/N_c$ suppression in either case. Thus, $cq$ recombination is the dominant heavy-quark recombination contribution to baryon production but is subleading for meson production. In this talk I will compare heavy-quark recombination predictions with data on $\Lambda_c$ asymmetries. The heavy-quark recombination contribution to the $\Lambda_c^+$ production cross section is

$$d\hat{\sigma}[gg \to \Lambda_c^+] = \sum_n d\hat{\sigma}[gg \to cq(n) + \bar{c}] \eta[cq(n) \to \Lambda_c^+].$$

The $\eta$ parameters are similar to the $\rho$ parameters described earlier. There are two possible color states, 3 and 6, and two possible spin states contributing at this order, for a total of four parameters for $\Lambda_c^+$ production:

$$\eta_3 = \eta[cu(1S_0^{(3)}) \to \Lambda_c^+], \quad \tilde{\eta}_3 = \eta[cu(3S_1^{(3)}) \to \Lambda_c^+],$$

$$\eta_6 = \eta[cu(1S_0^{(6)}) \to \Lambda_c^+], \quad \tilde{\eta}_6 = \eta[cu(3S_1^{(6)}) \to \Lambda_c^+].$$  

Isospin symmetry requires $\eta[cu(n) \to \Lambda_c^+] = \eta[cd(n) \to \Lambda_c^+]$. These parameters also scale with the heavy quark mass as $\Lambda_{QCD}/m_c$.

Techniques for calculating the short-distance cross sections $d\hat{\sigma}[\bar{q}g \to c\bar{q}(n) + \bar{c}]$ and $d\hat{\sigma}[gg \to cq(n) + \bar{c}]$ as well as explicit expressions can be found in Refs. [25, 28]. All these cross sections are strongly peaked in the forward direction of the initial light quark or antiquark. Define $\theta$ to be the angle between the light quark (or antiquark) in the initial state and the $cq$ (or $c\bar{q}$) in the center-of-momentum frame. The ratio of the recombination cross section to the dominant leading order fragmentation cross section, $gg \to c\bar{c}$, at $\theta = \pi/2$ is

$$\left. \frac{d\hat{\sigma}[\bar{q}g \to c\bar{q}(n) + \bar{c}]}{d\hat{\sigma}[gg \to \bar{c}c]} \right|_{\theta=\pi/2} \sim \frac{d\hat{\sigma}[gg \to cq(n) + \bar{c}]}{d\hat{\sigma}[gg \to \bar{c}c]} \left|_{\theta=\pi/2} \sim \alpha_s \frac{m_c^2}{\hat{s}}, \right.$$  

where $\hat{s}$ is the parton center-of-mass energy squared. When the $cq$ or $c\bar{q}$ emerges at right angles to the incoming partons, heavy-quark recombination is suppressed relative to fragmentation by a kinematic factor of $m_c^2/\hat{s}$. It is also suppressed when the charm quark is produced in the backward direction, $\theta = \pi$:

$$\left. \frac{d\hat{\sigma}[\bar{q}g \to c\bar{q}(3S_1^{(i)}) + \bar{c}]}{d\hat{\sigma}[gg \to \bar{c}c]} \right|_{\theta=\pi} \sim \frac{d\hat{\sigma}[gg \to cq(3S_1^{(i)}) + \bar{c}]}{d\hat{\sigma}[gg \to \bar{c}c]} \left|_{\theta=\pi} \sim \alpha_s \frac{m_c^2}{\hat{s}}, \right.$$  

$$\left. \frac{d\hat{\sigma}[\bar{q}g \to c\bar{q}(1S_0^{(i)}) + \bar{c}]}{d\hat{\sigma}[gg \to \bar{c}c]} \right|_{\theta=\pi} \sim \frac{d\hat{\sigma}[gg \to cq(1S_0^{(i)}) + \bar{c}]}{d\hat{\sigma}[gg \to \bar{c}c]} \left|_{\theta=\pi} \sim \alpha_s \frac{m_c^6}{\hat{s}^3}. \right.$$
Note that the backward suppression is greater when the $cq$ or $c\bar{q}$ is produced in a $^1S_0$ state. In the forward direction, there is no kinematic suppression:

$$\frac{d\sigma[\bar{q}g \to cq(n) + c]}{d\sigma[gg \to \bar{c}c]} \bigg|_{\theta=0} \sim \frac{d\sigma[qg \to cq(n) + \bar{c}]}{d\sigma[gg \to \bar{c}c]} \bigg|_{\theta=0} \sim \alpha_s .$$  \hspace{1cm} (10)

Heavy-quark recombination preferentially produces charm mesons and baryons in the forward direction of the incident light quark (or antiquark). The cross section is larger for charm particles that share a valence quark with one of the colliding hadrons because the structure functions of the valence quarks is largest. Thus, the heavy-quark recombination mechanism provides a natural explanation of the leading particle effect.

Another mechanism by which charm hadrons can be produced is by ordinary fragmentation of charm quarks produced in $cq$ or $c\bar{q}$ recombination. This process, called “opposite side recombination”, gives the following contributions to charm hadron production:

$$d\tilde{\sigma}[qg \to H + X] = \sum_{n, D} d\tilde{\sigma}[gg \to \bar{c}q(n) + c] \rho[\bar{c}q(n) \to \bar{D}] \otimes D_{c-H} ,$$ \hspace{1cm} (11)

$$d\tilde{\sigma}[\bar{c}qg \to H + X] = \sum_{n, \bar{B}} d\tilde{\sigma}[\bar{c}qg \to \bar{c}\bar{q}(n) + c] \eta[\bar{c}\bar{q}(n) \to \bar{B}] \otimes D_{c-H} .$$ \hspace{1cm} (12)

Here $\bar{B}$ is a charm antibaryon. The opposite side recombination mechanism can generate asymmetries even when there is no leading particle effect.

Fig. 3 compares calculations of the $D^\pm$ asymmetry using the heavy-quark recombination mechanism with data from the E791 experiment in which a 500 GeV $\pi^-$ beam is incident on a nuclear target [2]. In this analysis the feeddown from $D^*$ mesons is included but feeddown from excited $D$ meson states is neglected. The charm quark mass is set equal to 1.5 GeV and the renormalization and factorization scales are $\sqrt{p_T^2 + m_c^2}$. The parton distributions are GRV 98 LO [30] for the nucleon and GRV-P LO [31] for the pion. The strong coupling constant used is the one-loop expression for $\alpha_s$ with 4 active flavors and $\Lambda_{QCD} = 200$ MeV. Only the LO fragmentation diagrams are included in the calculation. The effect of NLO perturbative corrections can be taken into account by multiplying the LO cross section by a K factor of about 2 [10]. The fragmentation functions are $\delta$-functions times fragmentation probabilities taken from Ref. [32]. At fixed-target energies the single particle inclusive distributions $d\sigma/dx_F$ and $d\sigma/dp_T^2$ are better reproduced with $\delta$-function fragmentation functions rather than, for example, Petersen fragmentation functions [10].

In this calculation of the $D$ meson asymmetry the opposite side $\bar{c}q$ recombination contribution of Eq. (12) is not included, so the result is independent of the $\eta$ parameters. The $\rho$ parameters were determined by a global analysis of all measurements of $D$ meson asymmetries in fixed-target hadroproduction experiments [33]. Fits with one, two and three parameters were performed. (A four-parameter fit did not yield significantly better results than the three-parameter fit.) The results of all three fits are shown in Fig. 3. Note that even a fit with one parameter, $\rho_1 = 0.14$ and all other $\rho$ parameters set to zero, does a good job of describing the data in the forward region where heavy-quark
Charm production asymmetries from heavy-quark recombination

recombination is most important. Inclusion of other parameters is necessary to obtain agreement in the central region \( x_F \approx 0 \).

The universality of the \( \rho \) parameters is tested by looking at asymmetries of other \( D \) mesons as well as asymmetries in experiments with different beams. Fig. 4 compares the predictions of the heavy-quark recombination mechanism for \( \alpha[D^+] \) with data from the E791 experiment [2]. Fig. 5 shows data and a calculation of \( \alpha[D_s^-] \) for the WA89 experiment which has a 340 GeV \( \Sigma^- \) beam incident on a nuclear target [3]. These calculations use the same parameter sets as in Fig. 3 and the agreement with experiment is excellent.

Finally, the \( cq \) recombination mechanism for charmed baryons is tested by comparing to measurements of \( \alpha[\Lambda_c^+] \) in experiments with 500 GeV \( \pi^- \) beams from E791 [4] and 540 GeV \( p \) beams from SELEX [5]. The results are shown in Figs. 6 and

Figure 3. \( \alpha[D^-] \) vs. \( x_F \) and \( p_T^2 \) for a 500 GeV \( \pi^- \) beam on a nuclear target [2]. One-, two- and three-parameter fits are solid, dashed and dot-dashed curves, respectively.
Figure 4. $\alpha[D_{s}^{*-}]$ vs. $x_F$ for a 500 GeV $\pi^-$ beam [2]. Solid, dashed and dot-dashed curves are the same as Fig. 3.

Figure 5. $\alpha[D_{s}^{-}]$ vs. $x_F$ for a 340 GeV $\Sigma^-$ beam [3]. Solid, dashed and dot-dashed curves are the same as Fig. 3.

7. In the analysis of baryon asymmetries, the single nonvanishing $\rho$ parameter is chosen to be consistent with the one-parameter fit to $D$ meson asymmetries. Setting all the $\eta$ parameters to zero gives the asymmetry shown by the dotted lines in Figs. 6 and 7, which is generated entirely by opposite side recombination. Though this is adequate for the $\pi^-$ beam data, the $p$ beam data clearly requires an additional mechanism for generating baryon asymmetries. A one parameter fit with $\eta_3 = 0.22$ is shown by the solid lines in Figs. 6 and 7. The results of the calculation are in good agreement with
the baryon asymmetry measured in both experiments.

In this talk, I have shown that the heavy-quark recombination mechanism provides a natural mechanism for generating the observed charm meson and baryon asymmetries. There are four $cq$ recombination parameters and four $c\bar{u}$ recombination parameters which are universal. The heavy-quark recombination mechanism correctly accounts for observed $D$ meson and $\Lambda_c$ asymmetries. It is especially encouraging that the same set of $\rho$ parameters can be used to correctly describe $D$, $D^*$ and $D_s$ asymmetries in two different experiments with different beams. $\Lambda_c$ asymmetries in both $\pi^-$ and $p$ beams are well described by a fit with a single $\rho$ parameter that is consistent with $D$ meson data and a single $\eta$ parameter. In the future, a more detailed analysis of charm hadron asymmetries which thoroughly tests the universality of the $\rho$ and $\eta$ parameters should be performed. Once these universal parameters are determined, predictions for heavy-quark recombination cross sections for charm and bottom hadron production in a large variety of nuclear and particle physics experiments will be possible.
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References
