**$\Lambda_c^+/\Lambda_c^-$ Asymmetry in Hadroproduction from Heavy-Quark Recombination**

Eric Braaten, Masaoki Kusunoki  
*Physics Department, Ohio State University, Columbus OH 43210, USA*

Yu Jia  
*Department of Physics and Astronomy, Michigan State University, East Lansing MI 48824, USA*

Thomas Mehen  
*Department of Physics, Duke University, Durham NC 27708, USA and Jefferson Laboratory, 12000 Jefferson Ave., Newport News VA 23606*  
(Dated: September 3, 2018)

Asymmetries in the hadroproduction of charm particles directly probe power corrections to the QCD factorization theorems. In this paper, the heavy-quark recombination mechanism, a power correction that explains charm meson asymmetries, is extended to charm baryons. In this mechanism, a light quark participates in the hard scattering that creates a charm quark and they hadronize together into a charm baryon. This provides a natural and economical explanation for the $\Lambda_c^+/\Lambda_c^-$ asymmetries measured in $\pi N$ and $p N$ collisions.

The production of charm particles in fixed-target hadroproduction experiments exhibits large asymmetries that are commonly referred to as the “leading particle effect” [1, 2, 3, 4]. Charm hadrons that have a valence parton in common with the beam hadron are produced in greater numbers than other charm hadrons in the forward region of the beam. Asymmetries have also been observed in the production of light particles, such as pions and kaons. Asymmetries in charm particles are particularly interesting, because one can exploit the fact that the charm quark mass $m_c$ is much larger than $\Lambda_{QCD}$ to make closer contact with fundamental aspects of Quantum Chromodynamics (QCD). The large mass guarantees that even at small transverse momentum the production process involves short-distance effects that can be treated using perturbative QCD. Furthermore, the nonperturbative long-distance effects of QCD can be organized as an expansion in $\alpha_s/\Lambda_{QCD}$. There have been many measurements of the asymmetries for charm mesons [1]. Several proposed charm production mechanisms are able to explain these asymmetries by tuning nonperturbative parameters [5, 6]. Recent experiments have also measured the asymmetry for the charm baryon $\Lambda_c^+$ [2, 3, 4], defined by

$$\alpha(\Lambda_c) = \frac{\sigma(\Lambda_c^+) - \sigma(\Lambda_c^-)}{\sigma(\Lambda_c^+) + \sigma(\Lambda_c^-)}.$$  

The WA89 [2] and SELEX [3] experiments observe a large positive asymmetry for $\Lambda_c$ produced in the forward direction of $p$ and $\Sigma^-$ beams. These asymmetries are consistent with the leading particle effect, but much larger than those observed for charm mesons. For $\pi^-$ beams, the leading particle effect predicts no $\Lambda_c$ asymmetry, but a small positive asymmetry has been observed by the E791 [2] and SELEX [4] experiments. Explaining the $\Lambda_c$ asymmetries is a severe challenge for any of the proposed mechanisms for generating charm asymmetries [2, 3].

The factorization theorems of perturbative QCD [8] imply that the cross section for $\Lambda_c^+$ in a collision between two hadrons $h, h'$ is given by

$$d\sigma[hh' \rightarrow \Lambda_c^+ + X] = \sum_{i,j} f_{i/h} \otimes f_{j/h'} \otimes d\hat{\sigma}[ij \rightarrow c\bar{c} + X] \otimes D_{c \rightarrow \Lambda_c^+} + \ldots$$  

(2)

Here $f_{i/h}$ is a parton distribution, $d\hat{\sigma}[ij \rightarrow c\bar{c} + X]$ is the parton cross section, and $D_{c \rightarrow \Lambda_c^+}$ is the fragmentation function for a $c$ quark hadronizing into a $\Lambda_c^+$. The ellipsis represents corrections that are suppressed by powers of $\alpha_s/\Lambda_{QCD}/m_c$ or $\Lambda_{QCD}/p_{\perp}$. The leading order processes $gg \rightarrow c\bar{c}$ and $q\bar{q} \rightarrow c\bar{c}$ produce $c$ and $\bar{c}$ symmetrically. Charge conjugation invariance requires that $D_{c \rightarrow \Lambda_c^+} = D_{\bar{c} \rightarrow \Lambda_c^-}$, so $\alpha(\Lambda_c) = 0$ at leading order in perturbation theory. Next-to-leading order perturbative corrections [4, 10] generate asymmetries that are an order of magnitude too small to explain the data. Therefore the observed asymmetries in charm production must come from the power corrections to Eq. (2).

Recent work has shown that $D$ meson asymmetries in hadroproduction and photoproduction can be explained by an $O(\alpha_s/\Lambda_{QCD})$ power correction called heavy-quark recombination [11, 12, 13]. In the $c\bar{q}$ recombination process, a light antiquark $\bar{q}$ that participates in the hard scattering emerges with momentum of $O(\Lambda_{QCD})$ in the rest frame of the charm quark $c$ and the $c\bar{q}$ pair then hadronizes into a $D$ meson. In this paper, we extend the heavy-quark recombination mechanism to charm baryons. The most important process is $cq$ recombination, which is like $c\bar{q}$ recombination except the $\bar{q}$ is replaced by a light quark $q$ and the $cq$ diquark hadronizes into a charm baryon. We will show that this mechanism can explain the observed $\Lambda_c$ asymmetries.
The \( cq \) recombination cross section for a \( D \) meson is
\[
d\hat{\sigma}[\bar{q}q \to D] = \sum_n d\hat{\sigma}[\bar{q}q \to c\bar{q}(n) + \bar{c}\bar{q}] \rho[c\bar{q}(n) \to D]. \quad (3)
\]

The factor \( \rho[c\bar{q}(n) \to D] \) takes into account the nonperturbative hadronization of a \( cq \) with color and spin quantum numbers \( n \) into a final state that includes the \( D \) meson. Since the process is inclusive, the quantum numbers of the \( cq \) produced in the short-distance process can be different from that of the \( D \). The color and spin quantum numbers can both be changed by the emission of soft gluons in the hadronization process. The flavor of the recombining \( \bar{q} \) can also be different from that of the valence antiquark in the \( D \), but this requires creating a light quark-antiquark pair which is suppressed in the large \( N_c \) limit. Neglecting such contributions, the heavy-quark recombination cross section for \( D^+ \) depends on four independent parameters:
\[
\rho_1 = \rho[c\bar{d}(1S_0^{(1)}) \to D^+], \quad \rho_2 = \rho[c\bar{d}(3S_1^{(1)}) \to D^+], \quad \rho_3 = \rho[c\bar{d}(1S_0^{(8)}) \to D^+], \quad \rho_8 = \rho[c\bar{d}(3S_1^{(8)}) \to D^+]. \quad (4)
\]

Explicit expressions for these parameters in terms of nonperturbative QCD matrix elements can be found in Ref. [14]. They scale with the heavy quark mass as \( \Lambda_{\text{QCD}}/m_c \). Analogous parameters for \( D^0 \) and \( D^- \) mesons are obtained by using isospin symmetry and charge conjugation invariance, while parameters for \( D^{+\pm} \) states are related to those in Eq. (4) by heavy-quark spin symmetry. One might have expected the cross section in Eq. (4) to involve a convolution with a nonperturbative function that depends on the fraction of the light-cone momentum of the \( D \) meson carried by the light antiquark \( \bar{q} \). However, to lowest order in \( \Lambda_{\text{QCD}}/m_c \), only the leading moment of such a distribution is relevant. Therefore, the \( cq \) recombination cross sections are calculable using perturbative QCD up to an overall multiplicative factor \( \rho \).

The direct \( cq \) recombination process is not expected to be a significant source of charm baryons, since baryon production requires creating at least two light quark-antiquark pairs and is therefore suppressed by \( 1/N_c^2 \) relative to Eq. (4). The leading recombination mechanism for charm baryon production is \( cq \) recombination. A leading order Feynman diagram for this process is shown in Fig. 1. Creation of a light quark-antiquark pair is required for the \( cq \) to hadronize into either a charm meson or a charm baryon, so there is a \( 1/N_c \) suppression in either case. This factor makes \( cq \) recombination a subleading mechanism for charm mesons, but the leading mechanism for charm baryons. The \( cq \) recombination cross section for \( \Lambda^+ \) has the form
\[
d\hat{\sigma}[\bar{q}q \to \Lambda^+] = \sum_n d\hat{\sigma}[\bar{q}q \to c\bar{q}(n) + \bar{c}\bar{q}] \eta[c\bar{q}(n) \to \Lambda^+]. \quad (5)
\]

The factor \( \eta[c\bar{q}(n) \to \Lambda^+] \) takes into account the nonperturbative hadronization of a \( cq \) with color and spin quantum numbers \( n \) into a final state that includes the \( \Lambda^+ \). Isospin symmetry implies that \( \eta[c\bar{q}(n) \to \Lambda^+] \) is the same for \( q = u, d \), while it is suppressed by \( 1/N_c \) for \( q = s \). There are four possible color and spin states of the \( cq \) and therefore four independent \( \eta \) parameters:
\[
\eta_3 = \eta[c\bar{u}(1S_0^{(3)}) \to \Lambda^+], \quad \eta_4 = \eta[c\bar{u}(3S_1^{(3)}) \to \Lambda^+], \quad \eta_6 = \eta[c\bar{u}(1S_0^{(6)}) \to \Lambda^+], \quad \eta_6 = \eta[c\bar{u}(3S_1^{(6)}) \to \Lambda^+]. \quad (6)
\]

These parameters scale as \( \Lambda_{\text{QCD}}/m_c \), so \( cq \) recombination gives a power-suppressed contribution to the cross section.

The parton cross sections for \( cq \) recombination can be calculated using a straightforward generalization of the method described in Ref. [12] for \( cq \) recombination. Charge conjugation is applied to the line of spinors and Dirac matrices associated with the recombining light quark in Fig. 1. Angular momentum states can then be projected out using the operators of Ref. [12]. The amplitude is projected onto the appropriate color representation, which is either the 3 or 6 of \( SU(3) \). A simple prescription for projecting onto the leading moment of the light-cone momentum fraction of the \( q \) can be found in Ref. [12]. The parton cross sections for \( cq \) recombination are
\[
d\hat{\sigma}[\bar{q}q \to c\bar{q}(n) + \bar{c}\bar{q}] = \frac{2\pi^2\alpha_s^2m_c^2}{27s^3} F(n|\hat{s},\hat{t}), \quad (7)
\]
where \( \hat{s} \) and \( \hat{t} \) are the standard parton Mandelstam variables for \( c + q \to c\bar{q}(n) + \bar{c}\bar{q} \). The functions \( F(n|\hat{s},\hat{t}) \) for the four color and spin channels are
where $S = \hat{s}$, $T = \hat{t} - m_c^2$, and $U = \hat{u} - m_c^2$.

The parton cross sections for both $c\bar{q}$ and $c\bar{q}$ recombination are strongly peaked in the forward direction of the incoming $q$ or $\bar{q}$. For example, consider the ratio of the parton cross sections for $c\bar{q}$ recombination to that for $gg \to c\bar{c}$, which dominates the fragmentation term in the cross section. We define $\theta$ to be the angle between the incoming $q$ and outgoing $\bar{q}$ in the parton center-of-momentum frame. In the backward direction $\theta = \pi$, the ratio is suppressed by $m_c^2/S$ in both $3S_1$ channels and by $m_c^2/S^3$ in both $1S_0$ channels. At $\theta = \pi/2$, the ratio is suppressed by $m_c^2/S$ in all four channels. In the forward direction $\theta = 0$, there is no kinematic suppression of this ratio. The forward enhancement of the $c\bar{q}$ cross section gives charm meson asymmetries which are largest near $x_F \approx 1$. For $\Lambda_c$ produced in $pN$ collisions, the fragmentation cross section is smaller relative to $c\bar{q}$ recombination, so the asymmetry is large even for $x_F = 0.2$.

In addition to direct recombination of $c\bar{q}$ into $\Lambda_c^+$, we need to include two additional effects: $c\bar{q}$ recombination into a heavier charm baryon that subsequently decays into $\Lambda_c^+$ and the fragmentation into $\Lambda_c^+$ of a $c$ that is produced in a $c\bar{q}$ or $c\bar{q}$ recombination process. The cross sections for $\Lambda_c^+$ from the latter process, which we will call “opposite-side recombination”, are

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

$$\times \sum_B \rho[\bar{c}q(n) \to B] \otimes D_{c \to \Lambda_c^+} ; \quad (12)$$

$$d\hat{\sigma}[\bar{g}g \to \Lambda_c^+ + X] = \sum_n d\hat{\sigma}[\bar{g}g \to \bar{c}q(n) + c]$$

$$\times \sum_B \eta[\bar{c}q(n) \to B] \otimes D_{c \to \Lambda_c^+} . \quad (13)$$

The recombination factors in Eq. (12) and Eq. (13) are summed over $\bar{D}$ mesons whose valence partons are $\bar{q}\bar{q}$ and over antibaryons $\bar{B}$ whose valence partons include $\bar{c}\bar{q}$.

The feeddown from heavier charm baryons that decay into $\Lambda_c$ can be taken into account through inclusive $\eta$ parameters defined by

$$\eta_{inc}[cq(n) \to \Lambda_c^+] = \eta[cq(n) \to \Lambda_c^+]$$

$$+ \sum_B \eta[\bar{c}q(n) \to B] \otimes B \to \Lambda_c^+ + X . \quad (14)$$

The sum over $B$ includes all charm baryons that decay into $\Lambda_c^+$. They include $\Sigma_c^+$, $\Sigma_c^{++}$, and the negative-parity excitations $\Lambda_c^+ (2593)$ and $\Lambda_c^+ (2625)$ states, all of which have branching fractions into $\Lambda_c^+$ of nearly 100%.

In our analysis, we choose $m_c = 1.5$ GeV, use the one-loop running $\alpha_s$ with $\Lambda_{QCD} = 200$ MeV, and set the renormalization and factorization scales equal to $\sqrt{m_c^2 + m_c^2}$. We use the parton distributions GRV 98 LO in the proton and GRV-P LO for the pion. For the fragmentation function for $c \to \Lambda_c^+$, we use

$$D_{c \to \Lambda_c^+}(z) = f_{\Lambda_c^+} \delta(1 - z)$$

where $f_{\Lambda_c^+} = 0.076$ is the inclusive fragmentation probability. We also use delta-function fragmentation functions for the charm mesons, since this reproduces the shapes of their momentum distributions more accurately than Peterson fragmentation functions. In the opposite-side $\bar{c}q$ recombination cross section, Eq. (13), we include the $D$ and $D^*$ multiplets, but neglect the excited charm mesons. The best 1-parameter fit to all the $D$ meson asymmetries measured by E791 gives $\rho_1 = 0.15$ with $\rho_1 = \rho_8 = \bar{\rho}_8 = 0$. The fit can be improved by using additional parameters, but not dramatically. This value of $\rho_1$ is larger than the value $\rho_1 = 0.06$ obtained in Ref. 13 using Peterson fragmentation functions. Note that the sum of recombination parameters appearing in the opposite-side $\bar{c}q$ recombination cross section, Eq. (13), differs from the inclusive parameter in Eq. (14). The two are related if the the sum in Eq. (13) is dominated by the lowest mass $J^P = \frac{1}{2}^+$ and $\frac{3}{2}^+$ SU(3) multiplets. Then, using charge conjugation and a simple quark counting argument, we estimate $\sum \eta[\bar{c}q(n) \to B] \approx 3/2 \eta_{inc}[cu(n) \to \Lambda_c^+]$ for $q = u, d, s$.

Because of the large uncertainties associated with the parton distributions of the $\Sigma^-$, we focus on the $\Lambda_c$ asymmetry data from $\pi^-$ and $p$ beams measured by the E791 and SELEX experiments. The best 1-parameter fit to all this data yields $\eta_{\Lambda_c,inc} = 0.058$, with the other three inclusive $\eta$ parameters set to 0. The asymmetry variable $\alpha[\Lambda_c]$...
is shown as a function of $x_F$ for the pion beam in Fig. 2 and for the proton beam in Fig. 3. The 1-parameter fit agrees well with both the pion beam and proton beam data. The same fits also yield good agreement with observed $p_{\perp}$ dependence of the asymmetries. The fits can be improved by using additional parameters. In Figs. 2 and 3, we also show the predictions for $\alpha[\Lambda_c]$ if all the $\eta$ parameters are set to 0. Note that opposite-side recombination into $D$ mesons generates a positive asymmetry even if all the $\eta$ parameters vanish. It gives a reasonable fit to the pion beam data, but it severely underpredicts the asymmetry for the proton beam. Therefore, the large asymmetry from the proton beam is convincing evidence for the $cq$ recombination mechanism.

We have shown that heavy quark recombination provides a natural and economical explanation of the production asymmetries for charm baryons as well as charm mesons. Further work includes a more systematic analysis of all the charm asymmetry data from hadroproduction experiments and the prediction of charm and bottom asymmetries in present and future experiments. Previous analyses of $D$ meson asymmetries [12, 13] do not include contributions from opposite-side $cq$ recombination into charm baryons. This is particularly important for $D_s$ mesons since any asymmetry is generated by opposite side recombination.

E.B. and M.K. are supported in part by DOE grant DE-FG02-91-ER4069. Y.J. is supported by NSF grant PHY-0100677. T.M. is supported in part by DOE grants DE-FG02-96ER40945 and DE-AC05-84ER40150.

References:

[1] E. M. Aitala et al. [E791 Collaboration], Phys. Lett. B 371, 157 (1996); ibid. 411, 230 (1997); G. A. Alves et al. [E769 Collaboration], Phys. Rev. Lett. 72, 812 (1994); ibid. 77, 2392 (1996); M. Adamovich et al. [BEATRICE Collaboration], Nucl. Phys. B 495, 3 (1997); M. Adamovich et al. [WA82 Collaboration], Phys. Lett. B 305, 402 (1993).

[2] M. I. Adamovich et al. [WA89 Collaboration], Eur. Phys. J. C 8, 593 (1999).

[3] E. M. Aitala et al. [E791 Collaboration], Phys. Lett. B 495, 42 (2000).

[4] F. G. Garcia et al. [SELEX Collaboration], Phys. Lett. B 528, 49 (2002).

[5] R. C. Hwa, Phys. Rev. D 51, 85 (1995); O. I. Piskounova, Nucl. Phys. Proc. Suppl. 50, 179 (1996); E. Cuautle, G. Herrera and J. Magnin, Eur. Phys. J. C 2, 473 (1998); E. Norrbom and T. Sjostrand, Eur. Phys. J. C 17, 137 (2000); A. K. Likhoded and S. R. Slaboszynski, Yad. Fiz. 65, 132 (2002).

[6] R. Vogt and S. J. Brodsky, Nucl. Phys. B 478, 311 (1996); T. C. Gutierrez and R. Vogt, Nucl. Phys. B 539, 189 (1999).

[7] J. C. Anjos, J. Magnin and G. Herrera, Phys. Lett. B 523, 29 (2001); O. I. Piskounova, arXiv:hep-ph/0202005.

[8] J. C. Collins, D. E. Soper and G. Sterman, in Perturbative Quantum Chromodynamics, edited by A. H. Mueller, (World Scientific, Singapore, 1989).

[9] P. Nason, S. Dawson and R. K. Ellis, Nucl. Phys. B 327, 49 (1989); W. Beenakker et al., Phys. Rev. D 40, 54 (1989); Nucl. Phys. B 351, 507 (1991).

[10] S. Frixione, M. L. Mangano, P. Nason and G. Ridolfi, Nucl. Phys. B 431, 453 (1994).

[11] E. Braaten, Y. Jia and T. Mehen, Phys. Rev. D 66, 034003 (2002).

[12] E. Braaten, Y. Jia and T. Mehen, Phys. Rev. D 66, 014003 (2002).

[13] E. Braaten, Y. Jia and T. Mehen, Phys. Rev. Lett. 89, 122002 (2002).

[14] C. H. Chang, J. P. Ma and Z. G. Si, hep-ph/0301253.

[15] M. Gluck, E. Reya and A. Vogt, Eur. Phys. J. C 5, 461 (1998).

[16] M. Gluck, E. Reya and A. Vogt, Z. Phys. C 53, 651 (1992).

[17] L. Gladilin, hep-ex/9912064.