BEAUTY AND CHARM PRODUCTION AT FIXED-TARGET EXPERIMENTS*

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Fixed-target experiments continue to provide insights into the physics of particle production in strong interactions. The experiments are performed with different types of beam particles of varying energies, and many different target materials. Studies of beauty and charm production are of particular interest, since experimental results can be compared to perturbative QCD calculations. It is in this context that recent results from fixed-target experiments on beauty and charm production will be reviewed.

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1. Introduction

Although collider experiments have become the dominant approach to research in high-energy physics, ongoing efforts in fixed-target experiments continue to provide valuable insights that are complementary, and in many cases inaccessible, to collider experiments. In particular, many of the fixed-target experimental results on the study of heavy quark production cannot be reproduced in collider experiments due to the variety of beam particles and target materials that are available to fixed-target experiments. This trend is expected to continue for the foreseeable future as fixed-target experiments from the previous decade continue to publish results, and as a few new experiments begin to publish their findings.

Fixed-target experiments continue to make significant contributions to the study of heavy quark production, but are confronted by both theoretical and experimental challenges. With regard to beauty production, results can be compared to calculations that are based on perturbation theory as it is applied to Quantum Chromodynamics (QCD). However, the experiments are challenged by low beauty production cross sections. Perturbative QCD

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is also applicable to charm production. Here experiments have amassed large samples of charm particles, but theoretical calculations are plagued by large uncertainties (compared to beauty production). For studies of charm production the experiments often focus on non-perturbative effects, which are difficult to interpret in the context of QCD.

2. Overview of experiments and results

Table I shows the fixed-target experiments that have recent results on heavy quark production. The results are either unpublished and are being prepared for publication, or they have been published since my last review in 2002 of heavy quark production [1].

TABLE I

Overview of fixed-target experiments

Experiment	p_{beam} (GeV/c)	Beam	Target
HERA-B	920	p	C, Al, Ti, W
E866/NuSea E789 and E772	800	p	LH_2, LD_2, C, Ca, Fe, W, Ag, Au, and Cu dump
E781/SELEX	600 572	Σ^- and π^- p	C and Cu C and Cu
E791	500	π^-	C and Pt
E815/NuTeV	20–400	ν_μ, $\overline{\nu_\mu}$	Fe
E831/FOCUS	170	γ	BeO and Si
E835	<8.9	$\overline{p}$	hydrogen gas jet

The measurements that are presented in this paper are arranged by topic as follows:

- $\sigma(b\overline{b})$ cross section measurement
- possible observation of doubly-charmed baryons
- asymmetry measurements comparing particle/antiparticle production
- kinematic correlations in charm-pair events

Topics that are not included are measurements of the A-dependence in heavy-quark production, charm production with neutrinos, and recent measurements [2,3] from experiment E835 (see Matteo Negrini's contribution to this conference).

3. Beauty production

Measurements of beauty production are challenging for fixed-target experiments due to low production cross sections. However, despite the experimental challenges and large theoretical uncertainties, the measurements are important in that they probe heavy quark production in a regime where perturbative QCD calculations are applicable.

HERA-B has recently published [4] a measurement of $\sigma(b\bar{b})$, by measuring the cross section for 920 GeV proton–nucleus interactions using wire targets placed in the halo of the HERA proton beam. They reconstruct $J/\psi \to \mu^+\mu^-$ and $J/\psi \to e^+e^-$ decay vertices, and select J/ψ's that satisfy detachment cuts with respect to the wire targets. The J/ψ's are used to determine the number of $b-$hadrons decaying to J/ψ, as distinguished from the large prompt J/ψ background. The background comes from J/ψ production in the targets, and HERA-B uses this background to normalize $\sigma(b\bar{b})$ relative to other prompt J/ψ production measurements [5, 6].

With a sample of 8000 J/ψ's from their "Run 2000" data, HERA-B found 11 events that satisfied detachment cuts. Using these events, they published [4] a cross section of $32\ ^{+14}_{-12}$ (stat) $^{+6}_{-7}$ (sys) nb/nucleon. They are now analyzing J/ψ's in their "Run 2002/3" data. With 40 percent of the data analyzed, they have 38 ± 7 $J/\psi \to \mu^+\mu^-$ and 31 ± 9 $J/\psi \to e^+e^-$ events that satisfy detachment cuts. A significantly improved measurement of $\sigma(b\bar{b})$ is to be expected from this data.

4. Charm production

Studies of charm production benefit from the large data samples that have been collected by several experiments. Five new results are presented in this paper. The results come from Fermilab experiments that acquired data during a run in 1991, or during a subsequent run in 1996–1997. In 1991, experiment E791 acquired large charm samples using a 500 GeV/c π^- beam, and a recent publication [7] presents their analysis of the D^* production asymmetry. During the 1996–1997 run, the hadroproduction experiment SELEX ran with 572 GeV/c protons and 600 GeV/c Σ^- and π^- beams. They have published new results on the D_s production asymmetry [8], and the observation of doubly-charmed baryons [9]. The photoproduction experiment FOCUS also ran in 1996–1997, and they have a new result on $\Lambda_{\rm c}$ and $\Sigma_{\rm c}$ production asymmetries, which has been submitted for publication [11], and a published result on $D\overline{D}$ correlations [12].

Of the five results presented in this paper, the one that has received the most attention is the possible observation of doubly-charmed baryons by SELEX. Last year the collaboration published their results [9] at a time when they were reporting possible signals for three doubly-charmed baryon states. This year they claim to see five states. Four of the states are narrow, and are identified as $ccu(3460)$, $ccd(3443)$, $ccu(3540)$, and $ccd(3520)$. These states decay weakly. The fifth state is an excited ccu state with a strong decay to $ccd(3520)$. The lifetimes of the four narrow states are less than 33 femtoseconds, and about half of all Λ_c^+'s in the SELEX data come from the decay of these doubly-charmed baryons.

Table II [10] shows the number of doubly-charmed baryon candidates that SELEX observes for different beam particles. They claim that doubly-charmed baryons are produced by baryon beams, and within statistics protons are at least as effective as Σ^- hyperons at producing these states. This claim addresses the non-observation of doubly-charmed baryons by the photoproduction experiment FOCUS, which has approximately 12 times as many Λ_c events as SELEX and has looked for doubly-charmed baryons in a wide range of decay modes. Furthermore, E791 (π^- beam) has five times as many Λ_c events as SELEX and does not see doubly-charmed baryons. More research is required to confirm, or refute, the SELEX results.

TABLE II

Doubly-charmed baryon signal and sideband yields observed for different beam particles.

State	Σ^-	proton	π^-
luminosity fraction	0.77	0.13	0.10
$ccu(3460)$ signal	8	3	0
$ccu(3460)$ sideband	9	0	0
$ccd(3443)$ signal	6	2	0
$ccd(3443)$ sideband	10	2	1
$ccu(3540)$ signal	7	4	0
$ccu(3540)$ sideband	10	1	1
$ccd(3520)$ signal	18	4	0
$ccd(3520)$ sideband	18	1	1

One of the most striking effects observed in charm production is the *leading particle effect*. This effect is observed as an enhancement in the production rate of particles that have one or more valence quarks in common with a beam hadron (or target hadron) compared to the corresponding antiparticle production rate. The effect is usually presented as an asymmetry distribution as a function of x_F and p_T^2. Perturbative QCD predicts that particle/antiparticle asymmetries should be very small. However, the data typically display large asymmetries, which are attributed to non-perturbative QCD effects. This continues to be true for the most recent asymmetry measurements in hadroproduction, where E791 has published a D^* asymmetry measurement [7] and SELEX has published a D_s asymmetry measurement [8].

New asymmetry measurements, which have recently been submitted for publication [11], come from FOCUS. These measurements are the first measurements for $\Sigma_{\rm c}$ baryons, and may provide another test for a model that attempts to reconcile asymmetry measurements within the context of perturbative QCD by using a heavy-quark recombination mechanism [13].

FOCUS also has a recent publication on $D\overline{D}$ correlations [12], showing distributions for $\Delta\phi$, the angle between the D and $\overline{D}$ in the plane transverse to the beam, and $p_{\rm T}^2$, the transverse momentum squared for the $D\overline{D}$ pair. These distributions are important for heavy-quark production in QCD [14], since they provide useful comparisons to data in both hadroproduction and photoproduction. FOCUS shows that their $\Delta\phi$ and $p_{\rm T}^2$ distributions are in good agreement with a recent version of PYTHIA (version 6.203) [15].

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REFERENCES

[1] G. Cataldi *et al.*, (Eds.), *Heavy Quarks and Leptons 2002*, Frascati Phys. Ser. **28**, 17 (2002).
[2] M. Andreotti *et al.*, *Phys. Lett.* **B566**, 45 (2003).
[3] M. Andreotti *et al.*, *Phys. Rev. Lett.* **91**, 091801 (2003).
[4] I. Abt *et al.*, *Eur. Phys. J.* **C26**, 345 (2002).
[5] T. Alexopoulos *et al.*, *Phys. Rev.* **D55**, 3927 (1997).
[6] M.H. Schub *et al.*, *Phys. Rev.* **D52**, 1307 (1995).
[7] E.M. Aitala *et al.*, *Phys. Lett.* **B539**, 218 (2002).
[8] M. Kaya *et al.*, *Phys. Lett.* **B558**, 34 (2003).
[9] M. Mattson *et al.*, *Phys. Rev. Lett.* **89**, 112001 (2002).
[10] http://fn781a.fnal.gov/documentation/fnal.pdf
[11] J.M. Link *et al.*, `hep-ex/0311022`.
[12] J.M. Link *et al.*, *Phys. Lett.* **B566**, 51 (2003).
[13] E. Braaten, Y. Jia, T. Mehen, *Phys. Rev. Lett.* **89**, 122002 (2002).
[14] S. Frixione *et al.*, *Adv. Ser. Direct. High Energy Phys.* **15**, 609 (1998).
[15] T. Sjostrand *et al.*, *Comput. Phys. Commun.* **135**, 238 (2001).