Charm From Hyperons in the Future: Fermilab Experiment 781*

Michael Procario
Carnegie Mellon University

Abstract

Recent results from CERN experiment WA89 have shown that charmed baryons and particularly charmed-strange baryons have a significant cross section in $\Sigma^-$ beams. Fermilab experiment 781, which is currently under construction, will utilize this fact to pursue a broad program of high statistics studies of charmed baryons in the next Fermilab fixed target run.

I. INTRODUCTION

As the previous speaker has clearly shown, charmed baryons and particularly charmed-strange baryons are copiously produced in $\Sigma^-$ beams at $x_F > 0.2$. CERN experiment WA89 already has a sample of reconstructed charmed-strange baryons that is as good as any in the world, despite having a relatively small sample of charmed mesons. Fermilab experiment 781 will pursue this technique for studying charmed baryons with higher beam fluxes, larger acceptance, and a better vertex detector. This will make E781 a second generation charmed baryon experiment, and allow the systematic, in-depth study of charmed baryon production and decay physics.

The are a variety of physics goals in charmed baryon studies. The first is a complete understanding of the weak decays. Charmed baryons like charmed mesons have large QCD effects in their weak decays, and to understand these effects will require a broad program of measurements. The first measurements should be precision lifetimes of all weakly decaying charmed baryons. Today, only the $\Lambda_c^+$ is measured to better than 10%. Bigi has called for all weakly decaying charmed baryon lifetimes to be measured to better than 10%.

A very important complement to lifetimes are the semileptonic decays. Currently, CLEO and ARGUS have evidence for $\Lambda_c^+ \rightarrow X\Lambda\ell\nu$ and $\Xi_c^0 \rightarrow X\Xi^\prime\ell\nu$ decays and CLEO also has

*Invited talk at Second International Workdshop on Heavy Quarks Physics in Fixed Target, University of Virginia, October 1994
observed $\Xi^+_c \rightarrow X \Xi^0 \ell \nu$ decays. [3] There is currently no evidence of a semileptonic decay where the final state baryon is not a ground state hyperon.

Non-leptonic decays will be needed to sort out all of the nonfactorizing effects that are expected in charmed baryons. Only in the case of the $\Lambda^+_c$ have significant non-leptonic decays been observed. Many of these are multibody decays which may have resonance structure, but very little is known about that now.

The second major area of physics that can be addressed with charmed baryons is spectroscopy. Heavy Quark Effective Theory (HQET) has made a variety of predictions about the spectrum of charmed mesons, and similar predictions about baryons should be possible. There are extra degrees of freedom in the baryon sector which can be used to more stringently test the potential models, lattice calculations, and HQET predictions. Experimentally, most of the spectrum is unknown. Three of the four the ground state baryons are firmly established, as are the isospin 1 triplet of $\Sigma^*_c$'s. New results on the $\Omega_c$ [4], excited $\Lambda_c$'s [5], and the $\Xi'_c$ are statistically limited and will need to followed up. The rest of the spectrum is unknown.

The simple predictions of charm production from perturbative QCD do not agree with the data, although these predictions have been successfully corrected by modeling the non-perturbative effects. Most of this work has been done for mesons where the hadronization of the quark into the meson has been accounted for with fragmentation models. Currently, the production of charmed baryons seems to pose many more puzzles than have been seen in the mesons. NA32 has reported observing equal rates of $\Lambda_c$ and $\bar{\Lambda}_c$ at large $x_F$ from a $\pi^-$ beam, which is hard to understand in terms of perturbative QCD. WA89 has seen strong leading particle effects in a $\Sigma^-$ beam. They observe a much larger $\Sigma^0_c(cdd)$ signal than $\Sigma^+_c(cuu)$. [6] Both particles decay to $\Lambda_c^+$ and a charged $\pi$ so their acceptances are similar. One thing that is different is that $\Sigma^0_c(cdd)$ has the same light diquark $(dd)$ as the $\Sigma^-$.}

**II. THE DETECTOR**

E781 is a three-stage forward charge-particle spectrometer with particle identification and electromagnetic calorimetry. The detector has acceptance of $0.1 < x_F < 1.0$. The overall layout of the detector is shown in figure 4. There are a variety of reasons for choosing this geometry.

- At high $x_F$ the tracks have higher momentum and lower multiple scattering. This improves the vertex resolution, and allows us to trigger on large miss distance tracks.

- For the high momentum tracks we have a small solid angle to cover. This allows the use of a RICH with phototubes as the photon detector. Phototubes are easier to use and build than to TAMI or CsI photocathodes.
• It has been previously measured that the ratio of baryons to mesons increases with $x$ for strange particles, and the recent WA89 results have shown the same effect for charmed particles.

The philosophy of the detector’s design could be stated as: We know that there is charm there and we should optimize on signal/background not signal.

The beam is predominantly mixture of $\pi^-$ and $\Sigma^-$ with a small admixture of $\Xi^-$ and $\Omega^-$. The ratio, $n(\Sigma^-)/n(\pi^-)$ can be adjusted by varying the momentum that is accepted as shown in figure 2. We plan to run with a ratio $n(\Sigma^-)/n(\pi^-) \geq 1$. The $\Sigma$ flux will be $10^6$ MHz.

The first stage of the spectrometer has large acceptance with a 2.5 GeV/c momentum cutoff. This stage measures soft pions from $D^*$’s, $\Sigma_c$’s and other decays of excited charm states. It also can measure the tracks from the other charm particle which is produced at lower $x_F$ than the trigger charm particle, so that we can study charm pairs.

The second stage of the spectrometer has a 15 GeV/c momentum cutoff. This stage is used for the trigger, which will be fully discussed in the next section. There is a RICH detector with useful $p/K$ separation from 20 GeV/c to 225 GeV/c and $K/p$ separation from 40 GeV/c to 480 GeV/c. There is a transition radiation detector for electron identification.

The last stage measures the decay products of $\Lambda$’s that decay very far downstream. Charmed strange baryon decays can decay $\Xi^-$ and $\Omega^-$ which produce $\Lambda$’s very far downstream. This last stage is needed to achieve high efficiency for these decays.

The beam is measured with a silicon strip system to provide high accuracy predictions of $x - y$ position the primary vertex. The vertex region also has a silicon strip detector. This detector has 20 planes in 4 views to provide highly redundant tracking information to simplify track-finding and track-matching both in the online software filter and offline reconstruction. The performance of an eight plane system using an earlier generation of VLSI readout was run in a test beam. It achieved excellent hit resolution of 4$\mu$m for planes with 20$\mu$m pitch by interpolating the charge deposited in adjacent strips.

There are three lead glass photon detectors for the reconstruction of $\pi^0$'s and photons. One array of lead glass is associated with each stage of the spectrometer. The most downstream array will detect the radiative decay photons like $\Sigma^0 \rightarrow \Lambda \gamma$ or the not yet confirmed $\Xi'^c \rightarrow \Xi_c \gamma$.

### III. CHARM TRIGGER

The heart of E781 is the hardware trigger and online software filter. Both of these processes rely on the fact that the multiplicity is low in the second stage spectrometer and that these tracks are high enough momentum that they are well measured. The typical
multiplicity of non-charm events is 15 at the primary vertex but only 5 in our second stage spectrometer.

Two scintillator hodoscopes combined with matrix logic can count the number, measure the charge, and roughly estimate the momentum of tracks in the second spectrometer. By requiring 3 positive tracks in the second spectrometer, the hardware trigger rejects non-charm by a factor of 8-10. Typically the charmed baryon will contribute 2 of these positive tracks and the underlying event will contribute the other. Events passing this trigger are fully read out and passed on the online software filter.

The software filter runs in real time and only those event passing the filter are written to tape. This greatly reduces the offline analysis load after the experiment finishes its run, but it is critical that the quality of data is closely monitored to insure that data is not lost.

The software filter is topological looking for evidence of a secondary vertex. The filter searches for tracks after the second magnet. Those that are found are projected back into the vertex detector. Since the multiplicity is low after the second magnet the track finding is simplified there, and by looking only along the projected tracks in the vertex detector the track finding is also simplified in the vertex detector. These tracks are compared with the intersection of the beam track and the target foils. If any of the tracks miss this intersection by a significant amount then there is evidence of a secondary vertex.

The angular acceptance of the second stage of the spectrometer is 30 mrad and the targets are at most 1.5 mm thick, so the worst case geometric effect is 22\(\mu\)m. Multiple scattering errors are minimized by using only high momentum tracks. Simulations studies have shown that a 30\(\mu\)m cut on the miss distance keeps the non-charm background trigger rate below 1\%, if there are no tracking error. The fake trigger rate will be dominated by tracking errors not measurement errors.

A test was performed with an eight plane silicon vertex detector and single magnet spectrometer of similar angular acceptance as the full experiment. Data was taken with a 400 GeV pion beam striking a thick target (6\% \(\lambda_{int}\) of Al). Figure 3 shows the maximum miss distance per event from the test run. The measured rejection was good, and the E781 trigger should do better. A number of the events in the tail of the distribution hit confusion that will be helped by the stereo planes and the extra planes in the full vertex detector.

The miss distance filter is fully efficient for charmed baryon decays with lifetimes than 100 fs. It will also be very efficient for charmed meson decays, since the filter requirement is just a secondary vertex. The sample of charmed mesons should be comparable to the sample of charmed baryons. It should be very good for calibrating our detector, and we may be able to some small amount of physics with it.

Events which pass the miss distance filter are very useful for physics analysis. The filter indirectly requires requires a secondary vertex. In most analyses of charmed produced in fixed target experiments, the most powerful rejection of background is achieved by requiring
that the secondary vertex be separated from primary vertex. This is usually expressed as the distance from the primary vertex to the secondary divided by the resolution on the vertices ($L/\sigma$). A simulation of $\Lambda_c^+ \rightarrow pK^-\pi^+$ with $x_F = 0.3$ shows the effect of the miss distance trigger. Figure 4 shows that events with low $L/\sigma$ have been removed, so they events that pass our trigger are easier to analyze.

Some charmed baryons such as the $\Omega_c$ may have shorter lifetimes. We can also use other software filters designed around different event characteristics. In $\Omega_c$ and $\Xi_c$ decays there is multiple strangeness. Using the RICH to identify protons and kaons and select events having both, and have sufficient rejection of background to not need the miss distance requirement.

IV. YIELDS

E781 plans to accumulate more than $10^6$ reconstructed charmed hadrons, with over 100,000 in the large charmed baryon decay modes. Using NA32 $\pi^-$ production cross sections we can predict what E781 can expect from running with a $\pi^-$ beam. We scale up the cross section by 2 to account for our higher energy beam. The $x_F$ distribution is different. The power is 4.2 instead of 3.5. We use the same $p_t$ spectrum.

The assumptions about the run are 1000 hours of data with 1000 seconds of livetime per hour; 4% interaction probability; and that charmed production scales like $A^{1/3}$. The average $A$ of the E781 target is 32.8. The trigger and reconstruction efficiencies have been calculated. The trigger efficiency weighted by the cross section

$$\frac{d\sigma}{dx_F} = (1 - x_F)^{4.2}.$$ 

The reconstruction efficiencies were calculated using all necessary effects, such as detector resolution, multiple Coulomb scattering, primary and secondary vertex assignment, but not pattern recognition mistakes. The results for $\pi^-$ data are shown in table I.

The calculation of expected yields from the $\Sigma^-$ beam is more difficult than for the $\pi^-$ beam because the WA89 cross section analysis is not complete. We attempt to scale their yields by taking into account the relative acceptances, rejection factors and number of triggered events. The assumptions used are itemized below.

- The WA89 efficiency for $\Lambda_c \rightarrow pK^-\pi^+$ is 1% in 1991, 2.5% in 1993 and 1994 for $x_F > 0.2$.
- WA89 trigger rejected inelastic events five times the rate it rejected charm events.
- WA89 uses a $L/\sigma$ cut of 5, which is similar to the E781 online filter.
- E781 will have 15 times more interactions.
- E781 average efficiency per mode is 8%.
• The cross section at 600 GeV is 1.5 times greater than at 330 GeV.

Using these assumptions we arrive at the estimates in table [I]. These estimates are only good to a factor of 2-3.

E781 will be able to take data with both beams simultaneously. This will allow for systematic comparisons of the production from both beams. Since the software filter gives us the ability to find charm while still running, we will able to choose the beam that best optimizes our charmed baryon yields.

V. CONCLUSIONS

Charmed baryon physics is maturing. Results are now coming in from a variety of experiments on weak decays, spectroscopy and production mechanisms, which is stimulating theoretical work in the is area. However, most of the current results still have poor statistics compared to charmed mesons. The interesting questions like the differences in charmed baryon lifetimes, the possible leading particle effects, and many others will need higher statistics to be answered.

An experiment optimized for the study of charmed baryons can significantly improve this situation. E781 has set out to optimize the observation of charmed baryons through the use of a \( \Sigma^- \) beam, a very forward geometry, excellent particle identification, and a topological trigger. The yields expected in E781 will by on the order of 100,000 reconstructed charmed hadrons in the large decay modes. This sample will have similar numbers of charmed mesons and baryons and the charmed-strange baryons will be similar in number as the charmed baryons.
REFERENCES

[1] E781 Collaboration: Carnegie Mellon University, Fermilab, University of Iowa, University of Rochester, University of Washington, Petersburg Nuclear Physics Institute, ITEP(Moscow), IHEP(Protvino), Moscow State University, University of São Paulo, Centro Brasileiro de Pesquisas Físicas, Univeridade Federale de Paraíba, IHEP(Beijing), University of Bristol, Tel Aviv University, Max-Plank-Institut für Kernphysik-Heidelberg, Universidad Autonoma de San Luis Potosi.

[2] I.I. Bigi, CERN-Th.7370/94.

[3] H. Albrecht et. al. (ARGUS Collaboration), Phys. Lett. B269 p. 234 (1991).
H. Albrecht et. al. (ARGUS Collaboration) Phys. Lett. B303 p. 368 (1993)
T. Bergfeld et. al. (CLEO Collaboration) Phys. Lett. B303 p. 368 (1993)
J. Alexander et. al. (CLEO Collaboration) CLNS 94-1288.

[4] P. Frabetti et. al. (E687 Collaboration), Phys. Lett. B300 p. 190 (1993).

[5] H. Albrecht et. al. (ARGUS Collaboration), Phys. Lett. B317 p. 277 (1993).
P. Frabetti et. al. (E687 Collaboration), Phys. Rev. Lett. 72 p. 961 (1994).
K. Edwards et. al. (CLEO Collaboration), CLNS 94-1304.

[6] R. Werding (WA89 Collaboration), talk given at the International Conference on High Energy Physics, Glasgow, Scotland, 1994.

[7] S. Barlag et. al. (NA32 Collaboration), Phys. Lett. B247 113 (1990)
### TABLE I. E781 anticipated charm yields from $\pi^-$ beam

| Decay Mode          | NA32 $\sigma \cdot B$ | E781 efficiency | Expected E781 yield |
|---------------------|------------------------|-----------------|---------------------|
| $\Lambda_c^+ \to pK^-\pi^+$ | $180 \pm 36$          | 0.09            | 75,000              |
| $\Xi_c^+ \to \Xi^-\pi^+\pi^+$ | $130 \pm 95$          | 0.06            | 40,000              |
| $D^0 \to K^-\pi^+$    | $230 \pm 40$          | 0.08            | 86,000              |

### TABLE II. Estimates of expected charmed baryon yields from the $\Sigma^-$ beam in E781 scaled from WA89 yields

| Decay Mode          | WA89 (1991) | WA89 (1993) | Expected E781 yield |
|---------------------|-------------|-------------|---------------------|
| $\Lambda_c^+ \to pK^-\pi^+$ | 65          | $\sim 650$  | $\sim 50,000$      |
| $\Xi_c^+ \to \Lambda K^-\pi^+\pi^+$ | 42          | $\sim 400$  | $\sim 30,000$      |
| $\Xi_c^0 \to \Lambda K^-\pi^+$   | 32          | $\sim 600$  | $\sim 50,000$      |
FIG. 1. The layout of E781

Negative Beam Fraction at Pt=0, z=10m

FIG. 2. Particle fractions in Fermilab proton center hyperon beam
FIG. 3. Test run results for maximum miss distance from primary of high momentum tracks using an 8 plane silicon strip detector

FIG. 4. Monte Carlo results for the significance of $\Lambda_c^+$ vertices that pass the trigger