

# Limits on Charm Production in Hadronic Interactions near Threshold

J. H. Christenson, E. Hummel,<sup>(a)</sup> G. A. Kreiter, and J. Sculli  
New York University, New York, New York 10003

and

P. Yamin  
Brookhaven National Laboratory, Upton, New York 11973  
(Received 28 January 1985)

We present the results of an experiment to search for associated charm production near threshold in 13-GeV/ $c$   $\pi^-p$  interactions. A large-aperture proportional wire chamber spectrometer was sensitive to the decay fragments of the forward-produced  $D^{*-}$ 's expected from the two-body reactions  $\pi^- + p \rightarrow D^{*-} + \Lambda_c^+, \Sigma_c^+, \dots$ . The missing baryon mass was determined from the vector momenta of the incident pion and the candidate  $D^{*-}$ . No evidence for these reactions was found, which resulted in a 7-nb upper limit (95% confidence level) for each of the cross sections  $\sigma(\pi^-p \rightarrow D^{*-}\Lambda_c^+)$  and  $\sigma(\pi^-p \rightarrow D^{*-}\Sigma_c^+)$ .

PACS numbers: 13.85.Ni

The observation of charmed particles in hadronic interactions has proved to be a formidable task. At high energy, the production cross section is substantial but large backgrounds dominate the data. The recent development of high-resolution vertex detectors has considerably enhanced the sensitivity of fixed-target experiments at high energy, but only a small number of charmed decays have been observed.<sup>1</sup> We report the results of a search for charm production via the two-body reactions

$$\pi^-p \rightarrow D^{*-} + (\Lambda_c^+, \Sigma_c^+, \dots).$$

The cross sections and dynamics of these reactions are of interest in their own right, and the constraints imposed by the two-body kinematics allow a sizable reduction in background in the search for the charm signal. The cross sections for these exclusive channels are expected to rise from threshold at 10-GeV/ $c$  incident pion momentum, reach a maximum at about 13 GeV/ $c$ , and fall with momentum in a manner characteristic of meson-exchange reactions. In addition, the  $D^{*-}$  meson should be produced forward with a laboratory momentum peaked at 9 GeV/ $c$ , reflecting the fall-off in cross section with four-momentum transfer above its minimum value.

In this experiment, the  $D^{*-}$  was observed by detection of the secondaries from the well-known decay sequence

$$D^{*-} \rightarrow \bar{D}^0\pi^- \quad (64\% \text{ branching ratio}),$$

$$\bar{D}^0 \rightarrow K^+\pi^- \quad (3\% \text{ branching ratio}).$$

The unusually small  $Q$  value for the  $D^{*-}$  decay (5.7 MeV) provides a striking charm signature and greatly improves background suppression. Since the baryon is slow in the laboratory, its copious decay fragments are widely dispersed and escape detection, virtually eliminating combinatoric dilution of the charm sample.

However, the mass of the missing baryon is nonetheless determined by a measurement of the incident momentum of each beam particle, which reduces the background further and offers the promise of an inclusive study of the baryon mass spectrum. If the two-body cross section,  $d\sigma/dt$ , varies as  $e^{bt}$  with a slope parameter  $b = 2(\text{GeV}/c)^{-2}$ , the acceptance of the spectrometer is 1% for missing masses between 2 and 2.5 GeV/ $c^2$ , and falls to zero at 2.8 GeV/ $c^2$ . The acceptance does not depend sensitively on  $b$ , increasing slowly from 0.75% at  $b = 1(\text{GeV}/c)^{-2}$  to 1.5% for large  $b$ .

Previous searches at low energy have placed limits on the production cross section, the most sensitive being the work of Chung *et al.*,<sup>2</sup> that reports the cross section for  $\pi^-p \rightarrow D^{*-}\Lambda_c^+$  to be less than 70 nb (95% confidence level).

Our experiment was performed at the alternating-gradient synchrotron (AGS) at Brookhaven National Laboratory with the apparatus shown in Fig. 1. A 13-GeV/ $c$   $\pi^-$  beam, with a flux of  $(1-2) \times 10^7$  pulse in a momentum bite of 4%, was dispersed vertically 1% per in. immediately upstream of the apparatus. By determination of the altitude of the particle with a set of fine-grained scintillation hodoscopes, the momentum of each beam particle was measured to 0.25% (standard deviation). The small contamination of  $K^-$  and  $\bar{p}$  in the beam was eliminated by two threshold Cherenkov detectors filled with CO<sub>2</sub> at a pressure of 7 psi (gauge).

Secondary particles produced in a 40-in.-long liquid-hydrogen target were observed in a spectrometer built around a magnet with an aperture 10 ft wide, 3 ft long, and 2 ft high and providing a transverse momentum kick of 0.5 GeV/ $c$ . The trajectories of the  $K^+$  and  $\pi^-$  were each determined by a set of three proportional wire chambers (pwc's) placed on either side of the intense beam. Vector momenta from 3 to 8 GeV/ $c$

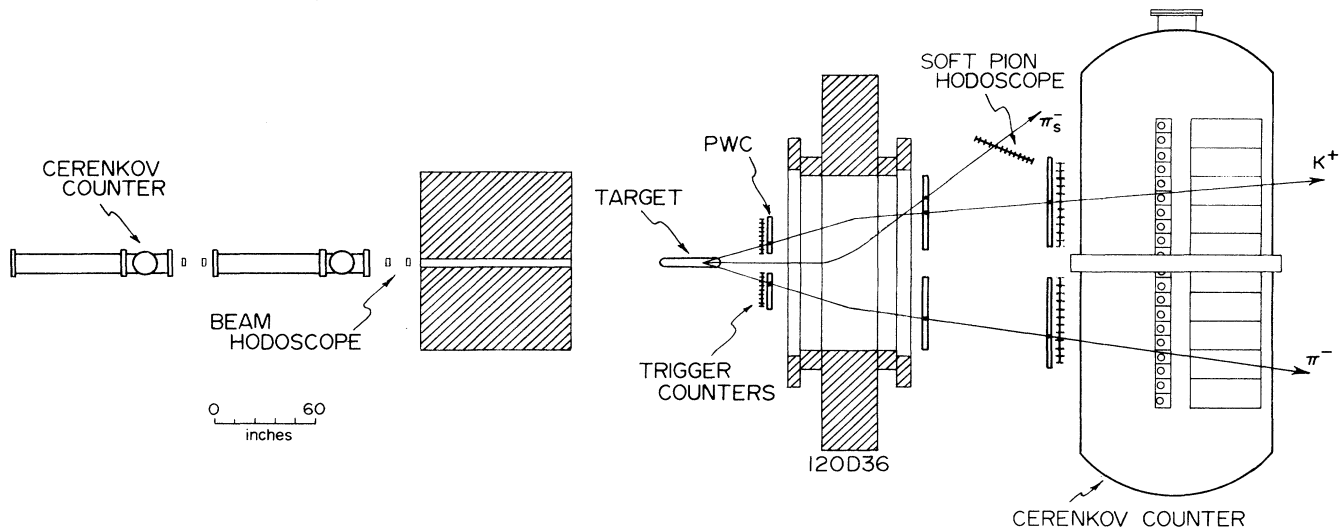


FIG. 1. Plan view of apparatus.

were measured with uncertainties  $\Delta p/p \sim 1\%$ ,  $\Delta\theta \sim 1$  mrad. Clean tracks were easily found, free of background from extraneous hits. The effective mass of the  $K^+\pi^-$  system was measured with an uncertainty of  $9 \text{ MeV}/c^2$ .

Pions were distinguished from kaons and protons in a large threshold Cherenkov detector at the rear of the spectrometer, outfitted with a pipe to allow the beam to pass through unnoticed. The detector was filled with 30 psi *a* (absolute) of Freon 12, resulting in a threshold of  $2 \text{ GeV}/c$  for pions and  $8 \text{ GeV}/c$  for kaons. The detector was segmented into forty independent cells to resolve signals from two particles passing through one side of the detector.

Since the decay  $D^{*-} \rightarrow \bar{D}^0 \pi_s^-$  has such a small  $Q$  value, the "soft" pion  $\pi_s^-$  has virtually the same velocity as the  $\bar{D}^0$ . It is produced at a small angle with respect to the beam and with a momentum of only  $0.5\text{--}1.0 \text{ GeV}/c$ . The particle passes between the PWC's in front of the spectrometer, has its path bent sharply by the magnet, and passes through the left-side PWC immediately after the magnet, finally striking a  $42 \times 42$ -element crossed hodoscope comprised of 1-in.-wide scintillation counters. A full 50% of the soft pions are detected in those events in which the  $\bar{D}^0 \rightarrow K^+\pi^-$  decay is accepted. By use of the  $K\pi$  vertex as the requisite third point on the soft-pion trajectory, the  $Q$  value was measured to  $0.7 \text{ MeV}$ . The missing baryonic mass was calculated from the vector momenta of the incident  $\pi^-$  and the  $K^+$ ,  $\pi^-$ , and  $\pi_s^-$  secondaries with a resolution of  $25 \text{ MeV}/c^2$ .

Of the two million beam interactions per AGS pulse, thirty thousand yielded a particle on each side of the spectrometer. Electronic requirements that the candidate  $\bar{D}^0$  secondaries be inbending particles with mo-

menta greater than  $1.5 \text{ GeV}/c$ , that the Cherenkov detector identify the negative particle as a pion and the positive particle as a kaon, and that a third particle be observed in the soft-pion detector reduced the trigger rate to  $\sim 500/\text{pulse}$ . At this rate, it was possible to calculate the sum of the  $K^+$  and  $\pi^-$  momenta in the on-line computer without serious dead time. By the requirement that this sum exceed  $6 \text{ GeV}/c$ , the rate at which events were recorded on tape was reduced to  $160/\text{pulse}$ . A total of 120 million triggers were recorded corresponding to a total incident flux of  $3 \times 10^{12}$  pions. 90% of the triggers originated in the hydrogen target.

The reconstruction strategy was designated to consider events without regard to particle multiplicity so as not to bias event selection against possible charm candidates containing baryon fragments. One quarter of the triggers had at least one  $K^+$  and one  $\pi^-$  track emanating from a common vertex in the path of the incident beam particle and one third of these contained a valid soft-pion trajectory that passed cleanly between the front PWC's. The final event sample is free of background from spurious hits or extra tracks. A detailed comparison of the data with a Monte Carlo simulation demonstrates that the resolution of the spectrometer has been fully realized in the data.

Several direct tests of the measurement accuracy of the apparatus were made. The observed momentum spectrum of the incident beam, for various apertures of the momentum defining collimator, was compared to that predicted by a Monte Carlo simulation of the beam. The data at very narrow apertures reveal a momentum resolution of  $0.25\%$ , as expected. Observation of the  $K^*(1430)$  in the  $K\pi$  mass spectrum of data taken without the soft-pion requirement demon-

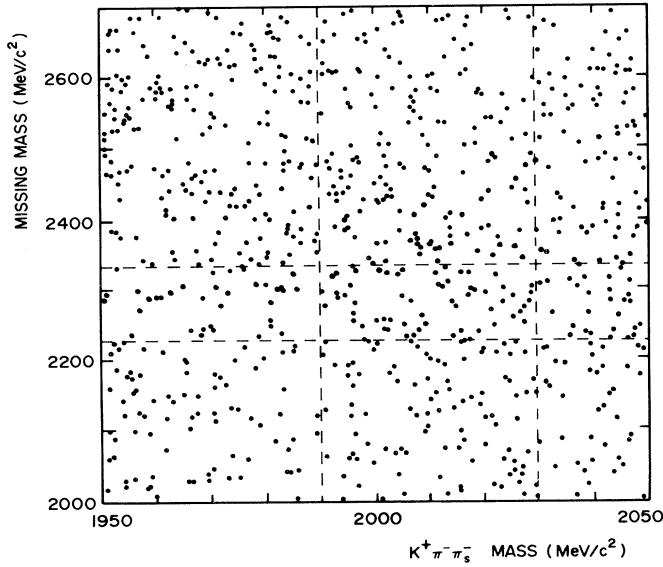


FIG. 2. Scatter plot of missing mass vs  $K^+\pi^-\pi_s^-$  mass for events with  $3.2 \text{ MeV} < Q < 8.2 \text{ MeV}$ . The dashed lines delineate  $4\sigma$  bands centered at the  $\Lambda_c^+$  (2282) and  $D^{*-}$  (2010).

strates that the mean effective mass determined by the PWC spectrometer is within 1% of that expected. The missing-mass spectrum observed in the reaction  $\pi^-p \rightarrow \pi^+\pi^-\pi_s^-X$  contains a clear neutron peak at  $892 \pm 7 \text{ MeV}/c^2$ . This  $48\text{-MeV}/c^2$  shift from the correct neutron mass is reduced kinematically to an uncertainty of less than  $15 \text{ MeV}/c^2$  at the mass of the  $\Lambda_c$ . The width of the peak agrees well with the estimated instrumental resolution.

A scatter plot of missing mass versus the  $K^+\pi^-\pi_s^-$  effective mass is given in Fig. 2 for all events with  $3.2 < Q < 8.2 \text{ MeV}$ . No structure is observed in the region of overlap of 4-standard-deviation wide bands centered at the  $D^{*-}$  and  $\Lambda_c^+$  masses. The  $K^+\pi^-\pi_s^-$  effective-mass spectrum of those events with missing mass greater than  $2 \text{ GeV}/c^2$  is shown in Fig. 3. No evidence is seen for  $D^{*-}$  production above a smooth continuum background, and a cross-section limit may be determined from the 230 events within  $\pm 20 \text{ MeV}/c^2$  ( $\pm 2\sigma$ ) of the  $D^{*-}$  mass at  $2010 \text{ MeV}/c^2$  and with a missing mass greater than or equal to the  $\Lambda_c^+$  mass. The cross-section sensitivity of the experiment, based on  $3 \times 10^{12}$  incident pions, a geometrical detection efficiency of 1%, a 64% branching ratio for the decay  $D^{*-} \rightarrow \bar{D}^0\pi_s^-$ , and a 2.4% branching ratio for  $\bar{D}^0 \rightarrow K^+\pi^-$ ,<sup>3</sup> is 2 events/nb. We find the inclusive  $D^{*-}$  production cross section to be less than  $2\sqrt{230}/2 \text{ eV/nb} = 15 \text{ nb}$  with 95% confidence.

The missing-mass spectrum of those events with a  $K^+\pi^-\pi_s^-$  mass within two standard deviations of the  $D^{*-}$  mass ( $1990 < m_{K\pi\pi} < 2030 \text{ MeV}/c^2$ ) and with

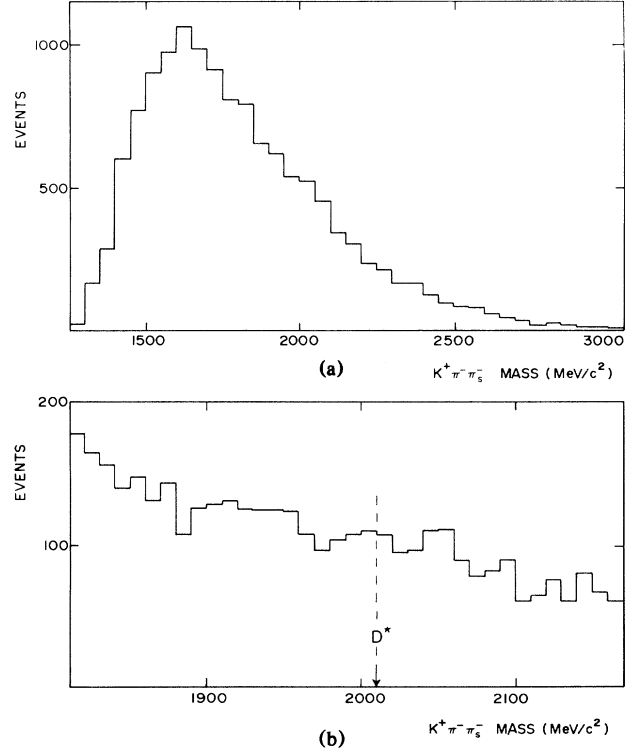


FIG. 3.  $K^+\pi^-\pi_s^-$  effective mass for events with  $3.2 \text{ MeV} < Q < 8.2 \text{ MeV}$  and missing mass greater than  $2000 \text{ MeV}/c^2$ . (a) Data plotted in  $50\text{-MeV}/c^2$  bins, (b) data in the region of the  $D^{*-}$  (2010) plotted in  $10\text{-MeV}/c^2$  bins. The mass resolution of the spectrometer is  $9 \text{ MeV}/c^2$ .

$3.2 < Q < 8.2 \text{ MeV}$  is shown in Fig. 4(b). No structure is seen in the  $\pm 50\text{-MeV}/c^2$  ( $\pm 2\sigma$ ) intervals centered at the  $\Lambda_c^+$  (2282) and the  $\Sigma_c^+$  (2420) masses. The data are consistent with a smooth background as seen in control bands on either side of the  $D^{*-}$  mass [Figs. 4(a) and 4(c)]. On the basis of the 47 events found in each interval, we find the cross sections for the reactions  $\pi^-p \rightarrow D^{*-}\Lambda_c^+$  and  $\pi^-p \rightarrow D^{*-}\Sigma_c^+$  each to be less than  $7 \text{ nb}$  with 95% confidence.

At Fermilab energies, the  $D$  production cross section is  $\sim 30 \mu\text{b}$ , about 100 times  $\psi$  production. Our results reveal that  $D$  production is smaller by at least a factor of 2000 and is no more than 7 times  $\psi$  production at low energy ( $\sqrt{s} = 5 \text{ GeV}$ ).<sup>4</sup> Calculations of hadronic  $\psi$  production that assume that the dominant subprocesses are gluon fusion and light-quark fusion agree well with measured cross sections down to energies just above threshold.<sup>4,5</sup> On the other hand, naked charm production seems not to be described simply by quark and gluon fusion. These two processes alone do not account for both the large cross section and the forward, large Feynman  $x$ , production observed at high energy.<sup>6</sup> Our experiment at low energy, where light-quark fusion should dominate, indicates that at least

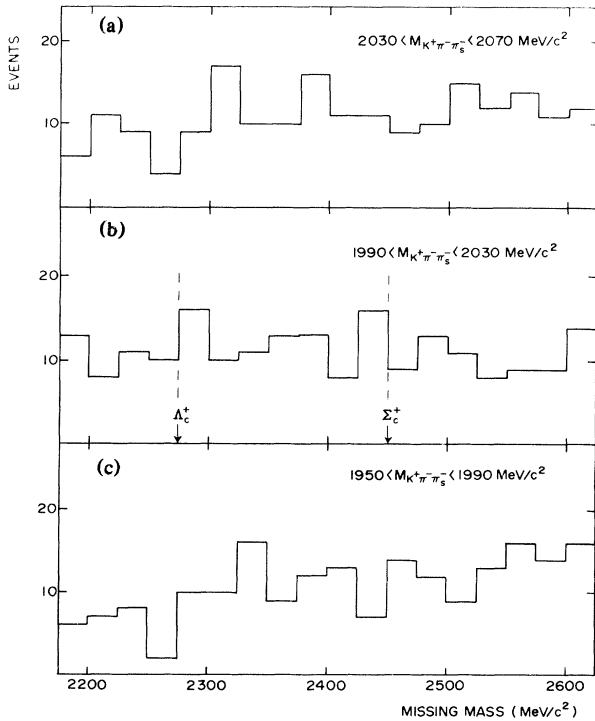


FIG. 4. Missing mass for events with  $3.2 \text{ MeV} < Q < 8.2 \text{ MeV}$  and  $K^+ \pi^- \pi_s^-$  mass restricted (b) to a  $4\sigma$  interval centered at the  $D^{*-}(2010)$  and (a), (c) in control regions above and below the  $D^{*-}(2010)$ .

15% of the charmed quark-antiquark pairs appear in bound states. Above threshold, at  $\sqrt{s} = 10 \text{ GeV}$ , bound-state production has already fallen to less than 1%.

We wish to thank the AGS staff, and particularly

Dave Dayton, for strong support throughout the experiment. We are grateful for the efforts of Bill Karp and Judi Fields at New York University. Ron Grobel and Mike Lauterbach helped in the construction and testing of the apparatus. The experiment was performed at Brookhaven National Laboratory and supported by funds from the Department of Energy and through National Science Foundation Grant No. PHY82-15319.

(a) Present address: AT&T Bell Laboratories, Whippany, N. J. 07981.

<sup>1</sup>M. Aguilar-Benitez *et al.*, Phys. Lett. **123B**, 98 (1983), and **123B**, 103 (1983), and **135B**, 237 (1984); R. Bailey *et al.*, Phys. Lett. **132B**, 230 (1983), and **132B**, 237 (1983), and **139B**, 320 (1984). See also H. Seebrunner *et al.*, in *Proceedings of the International Europhysics Conference on High Energy Physics, Brighton, England, 1983*, edited by J. Guy and C. Costain (Rutherford Appleton Laboratory, Chilton, England, 1983).

<sup>2</sup>S. U. Chung, *et al.*, Phys. Rev. Lett. **48**, 785 (1982).

<sup>3</sup>The  $D \rightarrow K \pi$  branching ratio was measured by I. Peruzzi *et al.*, Phys. Rev. Lett. **39**, 1301 (1977), and R. H. Schindler *et al.*, Phys. Rev. D **24**, 78 (1981). The  $D^{*-} \rightarrow \bar{D}^0 \pi^-$  branching ratio comes from G. Goldhaber *et al.*, Phys. Lett. **69B**, 503 (1977). See also C. G. Wohl *et al.* (Particle Data Group), Rev. Mod. Phys. **56**, S1 (1984).

<sup>4</sup>J. LeBritton *et al.*, Phys. Lett. **81B**, 401 (1979).

<sup>5</sup>C. E. Carlson and R. Suaya, Phys. Rev. D **18**, 760 (1978), and Phys. Lett. **81B**, 329 (1979).

<sup>6</sup>See, for example, B. L. Combridge, in *New Flavours, Proceedings of the Second Moriond Workshop, Les Arcs Savoie, France, January, 1982*, edited by J. Tran Thanh Van and L. Montanet (Editions Frontières, Gif-sur-Yvette, France, 1982).