ergy Commission under Contract No. AT(11-1)-3064.

†Present address: Fermi National Accelerator Laboratory, P. O. Box 500, Batavia, Ill. 60510.

‡Present address: P. O. Box 29246, Los Angeles, Calif. 90029.

§Present address: 36 Webb St., Lexington, Me. 02173.

[1]C. J. Bebek *et al.*, Phys. Rev. Lett. 30, 624 (1973).

[2]W. B. Atwood, private communication.

[3]A. Bodek *et al.*, Phys. Rev. Lett. 30, 1087 (1973).

[4]L. Hulthén and M. Sugawara, in *Handbuch der Physik*, edited by S. Flügge (Springer, Berlin, 1957), Vol. 39, p. 1.

[5]W. B. Atwood and G. B. West, Phys. Rev. D 7, 773 (1973).

[6]G. B. West, Ann. Phys. (New York) 74, 464 (1972).

[7]J. C. Adler *et al.*, Nucl. Phys. B46, 415 (1972).

[8]C. J. Bebek *et al.*, Phys. Rev. Lett. 32, 27 (1974).

[9]R. P. Feynman, Phys. Rev. Lett. 23, 1415 (1969).

[10]J. D. Bjorken and J. Kogut, Phys. Rev. D 8, 1341 (1973).

[11]A. H. Mueller, Phys. Rev. D 2, 2963 (1970).

[12]H. Burfeindt *et al.*, Phys. Lett. 43B, 345 (1973).

[13]H. Burfeindt *et al.*, Nucl. Phys. B74, 189 (1974).

Search for Charmed-Particle Production in 15-BeV/c π^+p Interactions*

C. Baltay, C. V. Cautis, D. Cohen, S. Csorna,† M. Kalelkar, D. Pisello, and E. Schmidt
Columbia University, New York, New York 10027

and

W. D. Smith and N. Yeh
State University of New York at Binghamton, Binghamton, New York 13901

A search for the production of charmed particles in 15-BeV/c π^+p interactions has been carried out. The search was sensitive to charmed particles in the 1.5 to 4.0 BeV mass range, with lifetimes $\lesssim 10^{-11}$ sec, decaying into a strange particle with up to eight additional pions. No evidence for the production of such particles was found.

The possibility of a new hadronic quantum number, charm, which had been suggested about ten years ago,[1] has recently received renewed attention.[2,3] In the simple quark model of the hadrons, this hypothesis can be interpreted as the existence of a fourth quark c carrying one unit of charm, in addition to the usual nonstrange quarks u and d, and the strange quark s. In order to be useful in canceling the strangeness-changing neutral currents, the c quark must have the same charge as the $I_z = +\frac{1}{2}$ u quark, and have weak couplings to the d and s quarks which are proportional to $\sin\theta$ and $\cos\theta$, respectively, where θ is the Cabibbo angle. The lowest-mass charmed baryons and mesons would thus be expected to decay predominantly into final states containing a strange particle. If charm is conserved in the strong interactions, then charmed particles would be produced in association with other charmed particles in strong processes.

We have carried out a systematic search for the production of charmed particles in π^+p interactions by looking for specific associated-production processes, as well as for inclusive-production processes, followed by the decay of the charmed particles into strange particles and pions. The distance traveled by the charmed particles before decay was assumed to be too short to be visible. The signal for the production and decay of such a particle would have been the accumulation of events at the mass of the particle in the effective-mass distribution of its decay products. The search was thus sensitive to new particles with lifetimes $\lesssim 10^{-11}$ sec. The total energy in the center of mass of the π^+p system, for incident pions with 15-BeV/c laboratory momentum, is 5.4 BeV.

The experiment has been carried out at the Stanford Linear Accelerator Center using an rf separated 15-BeV/c π^+ beam incident on the 82-in. bubble chamber filled with liquid hydrogen. A total of 866 000 pictures were taken and scanned, and all interactions were recorded. All interactions up to the highest multiplicity observed (fourteen outgoing charged tracks), with or without associated neutral-particle decays (vees), were measured on the Columbia University Hough-Powell Device operating in an automatic-pattern-recognition mode. About 750 000 events were measured. The measurements were processed by an event-finding program, followed by three-dimensional geometrical reconstruction and kinematic fitting to specific final states using our version of the programs TVGP and SQUAW.[4] Out of a total of ~ 500 000 events that successfully passed through all of the selection criteria up to the present time, a sample of 6005 events with $\Lambda \to p\pi^-$ and 9233 events with $K^0 \to \pi^+\pi^-$ decays was selected for this search.

The following specific charmed-particle-production processes have been looked for:

$$\begin{aligned} \pi^+ + p &\to B^{++} + \overline{M}^0, \\ &\to B^+ + \overline{M}^0 + \pi^+, \\ &\to p + M^+ + \overline{M}^0, \\ &\to \Delta^{++} + M^+ + M^-, \\ &\to \Delta^{++} + M^0 + \overline{M}^0, \end{aligned} \tag{1}$$

where B and M stand for charmed baryons or mesons, respectively. The search was sensitive to the following two- and three-body decay modes:

$$\begin{aligned} &B^{++} \to \Lambda\pi^+\pi^+,\ p\overline{K}^0\pi^+; \\ &B^+ \to \Lambda\pi^+,\ \Lambda\pi^+\pi^0,\ p\overline{K}^0,\ p\overline{K}^0\pi^0,\ pK^-\pi^+; \\ &M^+ \to \overline{K}^0\pi^+,\ \overline{K}^0\pi^+\pi^0,\ K^-\pi^+\pi^+; \\ &M^- \to K^0\pi^-,\ K^0\pi^-\pi^0,\ K^+\pi^-\pi^-; \\ &M^0 \to \overline{K}^0\pi^0,\ \overline{K}^0\pi^+\pi^-,\ K^-\pi^+,\ K^-\pi^+\pi^0; \\ &\overline{M}^0 \to K^0\pi^0,\ K^0\pi^+\pi^-,\ K^+\pi^-,\ K^+\pi^-\pi^0. \end{aligned} \tag{2}$$

In each of the Reactions (1), all final states that could result from any combination of the decay modes of the two charmed particles were kinematically fitted and used in the search except (i) final states with neither a K^0 nor a Λ^0, since a neutral decay vee was required to select the sample of events used in the search, and (ii) final states with two or more π^0's, since all events used in the search were required to satisfy kinematic fits.

For each combination of the decay modes considered for each of the Reactions (1), a two-dimensional scattergram was made, plotting the effective mass of the decay products of the first charmed particle against the effective mass of the decay products of the second. The scattergrams were made to cover the mass range from 1.5 to 4.0 BeV on both axes in 25-MeV bins, with a total of 10 000 bins per scattergram. Thus the background was spread out over many bins, while the signal for any of the Reactions (1) would be clustered in a few neighboring bins since the mass resolution in every case was better than the 25-MeV bin size. The scattergrams for each combination of decay modes were examined separately; they were then added together to make one scattergram for each of the Reactions (1), representing the sum of all the decay modes (2).

No statistically significant evidence was found for any of the Reactions (1). Upper limits for the number of events due to each reaction were taken to be the largest number of events above background in any four adjacent bins on each scattergram plus twice the standard deviation on the total number of events in the four bins. These numbers were converted to cross-section upper limits by taking into account the total pion flux, the efficiencies in the scanning, measuring, event finding, and kinematic fitting processes, the $K^0 \to \pi^+\pi^-$ and $\Lambda \to p\pi^-$ branching ratios, and the geometric efficiencies for detecting the K^0 and Λ decays. The resulting upper limits are given in Table I. These numbers should be interpreted as 95%-confidence-level upper limits on the product of the production cross section for each reaction and the sum of the branching ratios for the decay modes considered [Eq. (2)].

An inclusive search for charmed-particle production has been carried out in the following reactions:

$$\begin{aligned} \pi^+ + p &\to B^0 + X, \\ &\to B^{\pm} + X, \\ &\to B^{\pm\pm} + X, \\ &\to M^0 + X, \\ &\to M^{\pm} + X, \\ &\to M^{\pm\pm} + X, \end{aligned} \tag{3}$$

where B and M stand for charmed baryons and mesons, respectively, and X is any combination of charged or neutral particles. [Some of the

TABLE I. Upper limits on the production of charmed particles in specific associated-production reactions for the decay modes of Eq. (2).

Reaction	95% confidence level upper limit (μb)
$\pi^+ + p \to B^{++} + \overline{M}^0$	3.0
$\to B^{++} + \overline{M}^0 + \pi^+$	2.5
$\to p + M^+ + \overline{M}^0$	3.7
$\to \Delta^{++} + M^+ + M^-$	1.5
$\to \Delta^{++} + M^0 + \overline{M}^0$	2.6

TABLE II. 95%-confidence-level upper limits on inclusive production of charmed particles in the mass ranges 1.5–2.5 and 2.5–4.0 BeV.

Reaction	1.5 to 2.5 BeV	2.5 to 4.0 BeV
1. $\pi^+p \to B^0$ + anything		
$B^0 \to \Lambda\pi^+\pi^-$	11.0	8.8
$\Lambda 2\pi^+2\pi^-$	4.9	8.5
$\Lambda 3\pi^+3\pi^-$	0.9	2.3
$\Lambda 4\pi^+4\pi^-$	0.2	0.2
Sum Over Decay Modes	11.0	12.0
2. $\pi^+p \to B^+$ + anything		
$B^+ \to \Lambda\pi^+$	15.0	4.5
$\Lambda 2\pi^+\pi^-$	6.7	9.7
$\Lambda 3\pi^+2\pi^-$	1.1	5.2
$\Lambda 4\pi^+3\pi^-$	0.2	1.6
Sum Over Decay Modes	17.0	21.0
3. $\pi^+p \to B^-$ + anything		
$B^- \to \Lambda\pi^-$	5.7	2.0
$\Lambda\pi^+2\pi^-$	5.7	5.0
$\Lambda 2\pi^+3\pi^-$	0.9	2.7
$\Lambda 3\pi^+4\pi^-$	0.2	0.2
Sum Over Decay Modes	5.7	6.4
4. $\pi^+p \to B^{++}$ + anything		
$B^{++} \to \Lambda 2\pi^+$	11.0	8.7
$\Lambda 3\pi^+\pi^-$	6.6	6.5
$\Lambda 4\pi^+2\pi^-$	0.2	5.6
$\Lambda 5\pi^+3\pi^-$	0.2	0.8
Sum Over Decay Modes	11.0	14.0
5. $\pi^+p \to B^{--}$ + anything		
$B^{--} \to \Lambda 2\pi^-$	2.6	1.1
$\Lambda\pi^+3\pi^-$	0.8	1.8
$\Lambda 2\pi^+4\pi^-$	0.2	0.2
$\Lambda 3\pi^+5\pi^-$	0.2	0.2
Sum Over Decav Modes	2.6	2.0
6. $\pi^+p \to M^0$ + anything		
$M^0 \to K^0\pi^+\pi^-$	27.0	12.0
$K^0 2\pi^+2\pi^-$	18.0	7.6
$K^0 3\pi^+3\pi^-$	2.4	5.0
$K^0 4\pi^+4\pi^-$	0.4	0.4
Sum Over Decay Modes	27.0	14.0
7. $\pi^+p \to M^+$ + anything		
$M^+ \to K^0\pi^+$	20.0	5.7
$K^0 2\pi^+\pi^-$	35.0	17.0
$K^0 3\pi^+2\pi^-$	14.0	8.9
$K^0 4\pi^+3\pi^-$	0.7	2.4
Sum Over Decay Modes	35.0	19.0
8. $\pi^+p \to M^-$ + anything		
$M^- \to K^0\pi^-$	5.7	2.4
$K^0\pi^+2\pi^-$	12.0	9.0
$K^0 2\pi^+3\pi^-$	6.0	4.2
$K^0 3\pi^+4\pi^-$	0.4	0.4
Sum Over Decay Modes	12.0	9.0
9. $\pi^+p \to M^{++}$ + anything		
$M^{++} \to K^0 2\pi^+$	19.0	7.4
$K^0 3\pi^+\pi^-$	26.0	15.0
$K^0 4\pi^+2\pi^-$	2.8	7.6
$K^0 5\pi^+3\pi^-$	0.4	2.8
Sum Over Decay Modes	33.0	18.0
10. $\pi^+p \to M^{--}$ + anything		
$M^{--} \to K^0 2\pi^-$	6.8	1.0
$K^0\pi^+3\pi^-$	3.2	2.3
$K^0 2\pi^+4\pi^-$	0.4	0.4
$K^0 3\pi^+5\pi^-$	0.4	0.4
Sum Over Decay Modes	6.9	2.6

charge states of B and M in (3) cannot be formed by the simplest combination of quarks.] The sample of events described above with an associated $K^0 \to \pi^+\pi^-$ or $\Lambda^0 \to p\pi^-$ decay (or both) as identified by a three-constraint kinematic fit to the neutral vee was used in this search. No further kinematic fitting was done on these events for the inclusive search, so that events with any number of missing π^0's, neutrons, γ's, K^0's, etc., were included. The charged prongs were interpreted as pions. Using the measured momenta and angles of the pions and the fitted momentum and angle of the K^0 or Λ, the effective masses of the possible decay products of the charmed particles were calculated. Thus this search was sensitive to the decay modes listed in Table II.

The effective-mass distribution for any particular decay mode was made by combining events of all multiplicities, plotted from 1.5 to 4.0 BeV in 20-MeV bins. The mass resolutions in these plots were of the order of the bin size or better. A signal for charmed-particle production was taken to be an excess in the number of events in any one, two, or three adjacent bins above a smooth polynomial background fitted to each distribution. Several 2 and 3 standard deviation effects were observed. However, because of the large number of mass plots examined, none of these was considered statistically significant.

We thus feel that we found no convincing evidence for charmed-particle production. The upper limit for each decay mode was taken to be the number of events above background in the largest one-, two-, or three-bin fluctuation in any distribution, plus 2 times the standard deviation on the total number of events in those bins. These numbers were converted to cross section upper limits as described above. The upper limits, given in Table II, are the 95%-confidence-level limits on the production cross section times the decay branching ratio.

The upper limits for each of the Reactions (3), summing over all of the decay modes considered [Eq. (4)], are also given in Table II. It should be pointed out that these limits are not the sums of the limits quoted for the individual decay modes. They were obtained by taking the largest fluctuation in the combined mass distributions.

We thus conclude that we find no significant evidence for charmed-particle production in the 1.5 to 4.0 BeV mass range in a statistically very large sample of π^+p interactions in a search sensitive to a large number of possible decay modes.

It might be worth pointing out that the upper limits obtained in this search are of the order of 1% of the cross sections of similar strange-particle production processes at similar Q values.[5]

A number of other experimental searches for charmed-particle production are now in progress, but no results are available yet from any of them. The only previously published search[6] for charmed particles was sensitive only to longer-lived neutral states ("vees") produced in 400-GeV/c pp collisions and obtained upper limits on their production cross section one to two orders of magnitude larger than the results presented here.

We thank the operating crews of the 82-in. bubble chamber and the beams at Stanford Linear Accelerator Laboratory, the scanning groups of Columbia University and the State University of New York at Binghamton, and the Columbia University Hough-Powell Device staff for their efforts on this experiment.

*Research supported by the National Science Foundation.

†Present address: University of Washington, Seattle, Wash. 98105

[1]J. D. Bjorken and S. L. Glashow, Phys. Lett. 11, 255 (1964).

[2]S. L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D 2, 1285 (1970).

[3]A. De Rújula and S. L. Glashow, Phys. Rev. Lett. 34, 46 (1975), and other articles in the same issue.

[4]For experimental details, see M. Kalelkar, Ph.D. thesis, Columbia University (Nevis Report No. 207), 1975 (unpublished); S. Csorna, Ph.D. thesis, Columbia University, 1975 (unpublished).

[5]For example, in this experiment, the inclusive K^0 and Λ^0 production cross sections are ~ 2300 and ~ 850 μb, respectively.

[6]T. Ferbel, in *Experimental Meson Spectroscopy —1974*, AIP Conference Proceedings No. 21, edited by D. A. Garelick (American Institute of Physics, New York, 1974), p. 393

Cross Sections for "Diffractive" $p+p\rightarrow p+X$ from 100 to 400 GeV*

R. D. Schamberger, Jr., J. Lee-Franzini, and R. McCarthy
State University of New York at Stony Brook, Stony Brook, New York 11794

and

S. Childress and P. Franzini
Columbia University, New York, New York 10027
(Received 16 December 1974)

We have measured the cross section for $p+p\rightarrow p+X$ for M_X^2 up to a constant fraction of s. We observe no rise for $130 < E < 400$ GeV. The inelastic cross section for $0 < M^2 < 0.06s$ is 2.50 ± 0.05 mb for various values of s from 263 to 752 GeV^2.

The recent observation at the CERN intersecting storage rings (ISR)[1] of the increase at high energy of the total cross section for proton-proton scattering has led to many speculations on the mechanism responsible for this rise. A candidate for such a mechanism is the so-called "diffractive process," $p+p\rightarrow p+X$, which shows an enhancement at low mass of X. For very low masses ($M^2\sim 2$–3 GeV^2), this enhancement is known to have a constant cross section in the energy range from 30 to 300 GeV.[2,3] Triple Regge[4] phenomenology suggests a contribution to the low-M^2 spectrum of the form A/M^2. Integration of this contribution up to any constant fraction of the square of the total available energy s gives a cross section increasing as $A\ln(s)$. Since the total diffractive cross section has been variously measured[2,5] to be $2\times(1.7$–$2.6)$ mb, one might expect to observe a very large relative increase in this small cross section for the s range ~ 200 to ~ 800 GeV^2. We have performed an accurate measurement of the inelastic scattering cross section $d^2\sigma/dt\,dM^2$ for the reaction $p+p\rightarrow p+X$, covering the range of the square of the four-momentum transferred to the target proton $0.02 \lesssim -t \lesssim 0.22$ (GeV/c)^2, the range in invariant M^2 of X being $m_p^2 < M^2 < 0.13s$ and at values of the square of the center-of-mass energy $s = 244$ to 752 GeV^2.

We present here the results of our cross-section measurements. No rise with s is observed.

We have studied the reaction $p+p\rightarrow p+X$ at the internal target area of Fermilab by using the in-