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Limits on Production of Charmed Particles by Antiprotons and Pions*

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We have searched in the mass range $1.8 < M < 2.5$ GeV for narrow resonances produced by antiprotons and pions of momentum 12.4–15.0 GeV/c interacting in a carbon target. We present upper limits on the production cross section times branching ratio for charmed mesons decaying into two charged particles.

We report here the results of a search for narrow resonances in the mass range[1] $1.8 < M < 2.5$ GeV produced in $\bar{p}$- or π^--nucleon interactions at a center-of-mass energy of ~5 GeV. The current interest in charmed mesons directly stimulated the present experiment. The reaction

$$\bar{p} + N \to D^0 + \bar{D} \tag{1}$$

is an especially favorable source of such particles. (Here D is the pseudoscalar charmed meson, as in Gaillard *et al.*, Ref. 1.) It can reasonably be expected that the exclusive production cross section would rise rapidly from threshold, as it does with other mesons. Correspondingly, the reaction would provide a source of such particles with a minimum of background. No search of comparable sensitivity has been reported for either the $\bar{p}N$ or π^-N initial state.[2]

The experiment was carried out at the Brookhaven National Laboratory alternating gradient synchrotron (AGS) in the high-energy unseparated beam. The apparatus, Fig. 1, consisted of a double-arm spectrometer symmetric about the beam axis. The angle of each arm was fixed at 18°, and the beam momenta used were 12.4 and 15.0 GeV/c. The acceptance of D's produced in the exclusive reaction (1) was a fairly sharp function of the mass for a given beam momentum. The angle of 18° maximized the acceptance at a mass of about 2.3 GeV for the detected particle. The incident beam was operated at a flux of ~10^7 particles per beam spill within a momentum bite of ± 2%. The fraction of the beam which was antiproton was about 5×10^{-3} at 12.4 GeV/c and 3×10^{-3} at 15 GeV/c. A high-pressure differential Čerenkov counter identified antiprotons with a typical pion rejection factor of 5×10^{-4}.

A large geometrical acceptance (2×10^{-2} sr per

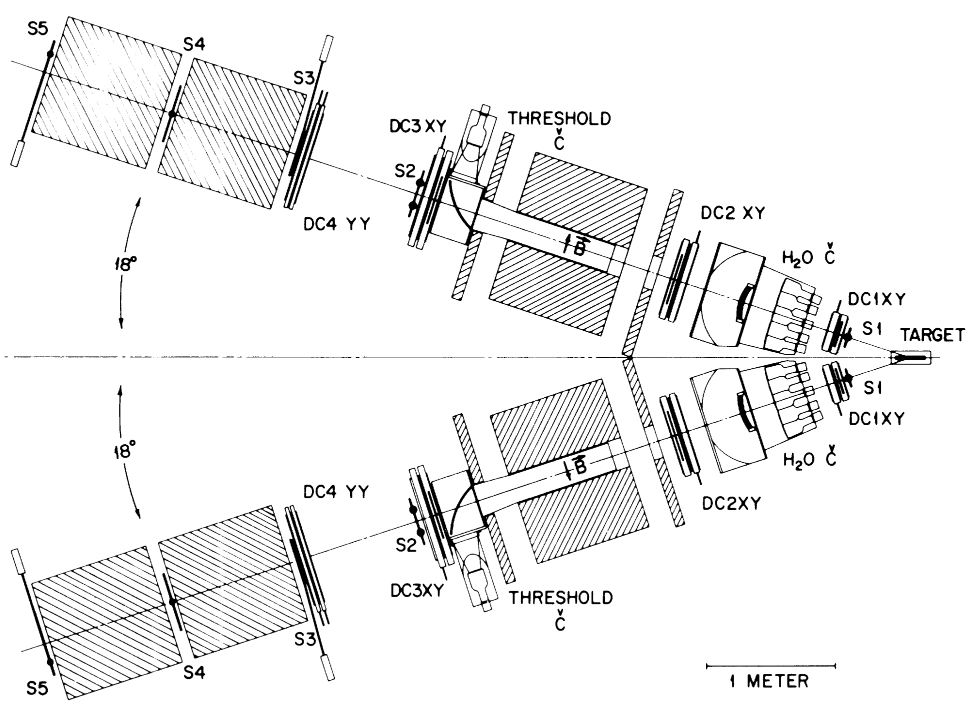

FIG. 1. Plan view of the spectrometer. DC1–DC4 indicate location of drift chambers in each arm, $S1$–$S5$ are scintillation counters used in triggering apparatus. Each of the differential water Čerenkov counters is labeled H_2O Č and each of the atmosphere pressure gas Čerenkov counters is marked threshold Č.

arm) for secondary particles with transverse momentum $p_\perp \gtrsim 0.5$ GeV/c was achieved through a compact spectrometer design. Each spectrometer arm was equipped with trigger scintillation counters, drift chambers and magnet for momentum and angle measurements, and Čerenkov counters and iron muon filters for particle identification. The bending plane of the spectrometer was vertical, at right angles to the production plane. This feature served to keep the low-momentum cutoff as sharp as possible, thus helping to restrict the trigger to the desired high-mass pairs. Data were taken under two trigger conditions: (a) "$\bar{p}$" runs in which either $\bar{p}\times(L\times R)$ or $(L\times R)\times(\mu_L+\mu_R)$ triggered the system, and (b) "π^-" runs with an $(L\times R)$ trigger, in which $\bar{p}$ and μ events were tagged. Here $\bar{p}$ refers to a signature from the beam Čerenkov counters, L and R refer to charged particles traversing the left and right spectrometer arms as defined by scintillation counters, and μ_L and μ_R refer to coincident signals from the scintillation counters behind the iron filters. The beam flux was lowered and the target size was reduced from 9 in. of carbon for the $\bar{p}$ runs to 3 in. for the π^- runs.

The trajectory of particles upstream of the magnet was determined by two sets of drift chambers mounted 50 in. apart. Each set consisted of an XX' module and a YY' module, where the sense wires in the X' plane were offset by half a cell relative to the X plane, in order to resolve left-right ambiguities.[3] At each chamber the horizontal and vertical coordinates of the particle trajectory were measured with an error $\sigma \simeq 0.5$ mm. This value has been determined from data and straight-through tracks, and includes systematic effects. Two more sets of chambers, an XX' and a YY', 30 in. from the magnet exit face, and one YY', 50 in. further downstream, measured the trajectory of the particle behind the magnet, providing sufficient information to determine the particle momentum. The $\int \vec{B}\cdot d\vec{l}$ of the magnet was approximately 440 MeV/c, which gave a low-momentum limit of about 1.5 GeV/c for the particles which trigger the system.

Particle identification was a difficult problem for a number of reasons. The range of momenta accepted was quite large (1.5 to 5 GeV/c); and discrimination was required for particles as slow as $\beta = 0.95$. The phase space of secondary particles was rather large, with maximum angles of 0.1 rad to the center line of the arm; and spatial limitations imposed by the spectrometer size constrained the number and types of counters which could be used.

A threshold Čerenkov counter fitting in the magnet gap and filled with Freon 12 at atmospheric pressure was used to separate pions from kaons and protons above ~3 GeV/c. Separation of kaons and protons at all momenta, and pions and kaons below 3 GeV/c, was obtained with a broad-band differential Čerenkov counter of new design. This was a wide-aperture counter, with a 1.5-in.-thick 12-in.-diam water radiator, which used a short-focal-length spherical mirror to image the Čerenkov light at the entrance to the light-collecting funnels. Light emitted by particles in the velocity range $\beta = 0.95$ to 1.0 was collected over a 2-in.-wide ring in the focal plane. The novelty of the design consisted of devising a method to measure with uniform precision the average radius of the light ring over the 2-in. band for the large range of particle angles accepted by the spectrometer. This radius measurement, together with the momentum measurement, provided particle identification.

The results being reported in this Letter include data from a π^- run at 15 GeV/c and $\bar{p}$ runs at 12.4 and 15 GeV/c. In the π^- run, the total flux was 3×10^{11} π^-'s impinging on a 16-g/cm^2 carbon target; in the $\bar{p}$ runs, there was a total of 2×10^{10} $\bar{p}$'s on a 50 g/cm^2 target. The geometrical acceptance of the apparatus was typically 10^{-3} for inclusive production, assuming a flat dependence of the cross section on the Feynman scaling variable x. Only a fraction of the events which triggered the apparatus had a reconstructible track in each arm and useful Čerenkov-counter information. The recovery efficiency, which included such losses, was around 10%, but depended strongly on the beam intensity.

With use of the measured momentum and angle of the two particles, the effective mass was calculated. Identification of the decay products was based on counter information. Since the particle identity was often ambiguous, more than one assignment for a given track was allowed, thus causing one event to appear in more than one mass plot. The mass resolution has been calculated to be $\pm1.2\%$ for a $K\pi$ mass of 2.3 GeV. Figure 2 displays the combined $K^\pm\pi^\mp$ mass spectrum for events with incident antiprotons and, separately, the $K^+\pi^-$ and $K^-\pi^+$ mass spectra for events produced with the pion beam. Besides the histograms shown, similar distributions have been made of all possible combinations of π, K, and p, for both incident $\bar{p}$ and π^-. No significant peak has been observed in any mass distribution.

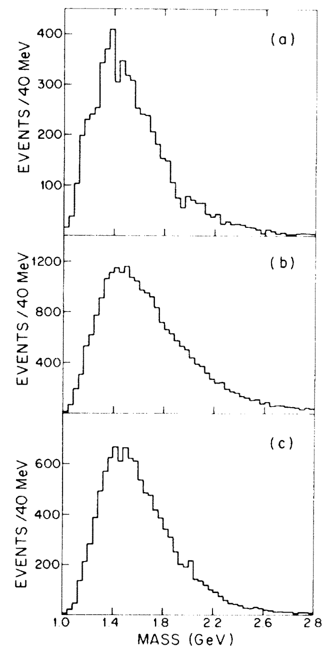

FIG. 2. (a) $K^\pm\pi^\mp$ invariant-mass distribution from the $\bar{p}N$ data. (b) $K^+\pi^-$ invariant-mass distribution from the π^-N data. (c) $K^-\pi^+$ invariant-mass distribution from the π^-N data.

Upper limits were calculated for the cross section times branching ratio (σB) for the production of a narrow high-mass resonance. These limits assume that a 4-standard-deviation effect in a mass interval of four times the experimental resolution would have been observed. Also required were the Monte Carlo acceptance of the apparatus,[4] the estimates of the recovery efficiency, the measured beam flux, and the number of target nucleons. Table I shows typical cross-section limits obtained for the various decay-production channels. Since the beam momentum was chosen to search for charmed mesons with mass of 2.3 GeV, the cross-section limits are higher by as much as a factor of 8 at masses near 1.9 GeV. The highest mass which could be pair-produced was about 2.7 GeV for $\bar{p}N$ and about 2.3 GeV for πN interactions. Since $\mu^+\mu^-$ events were accepted by the trigger during both $\bar{p}$ and π^- runs, the total pion flux was 5×10^{12} for these events. One candidate for the decay $J\to\mu^+\mu^-$ has been observed in this sample. If this event is in fact a J decay, the corresponding σB for the reaction

$$\pi^- + N \to J + X, \quad J \to \mu^+ + \mu^-, \tag{2}$$

is 4×10^{-35} cm^2.

We gratefully acknowledge the assistance of the

TABLE I. Upper limits for inclusive production cross section times branching ratio in $\bar{p}N$ and π^-N interactions. The cross section corresponding to one event in the $\bar{p}N$-data sample ranges from 110 nb at $M_{K\pi}$ =1.9 GeV to 20 nb at $M_{K\pi}$ =2.3 GeV. For the π^-N sample, one event represents about 4 nb in this mass region.

Decay mode	Mass (GeV)	Upper limit (μb/nucleon) $\bar{p}N$	π^-N
$K^+\pi^- + K^-\pi^+$	2.3	0.8	
$K^+\pi^- + K^-\pi^+$	1.9	6.0	
$K^+\pi^-$	2.3	0.6	0.3
$K^+\pi^-$	1.9	4.4	0.8
$K^-\pi^+$	2.3	0.6	0.15
$K^-\pi^+$	1.9	4.0	0.5
$\pi^+\pi^-$	2.3	0.6	0.2
K^+K^-	2.3	0.5	0.15
K^-p	2.3	0.9	0.3
$\bar{p}p$	3.0	0.3	0.1

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Precocious Scaling: Evidence for Field Theory

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We derive expressions for the Wilson coefficient functions in terms of moments of $W_{1,2}$ treating target-mass effects exactly. An analysis of existing electroproduction data indicates that scaling in the Wilson sense sets in for Q^2 as low as 2–3 GeV^2. The effective charge $\alpha_s(Q^2)$ appears to be small and may have Q^2 dependence only within experimental errors. We consider these results as evidence that the underlying theory of strong interactions is a field theory.

The discovery of the asymptotically free character of the non-Abelian gauge theories has inspired a renewed hope that hadronic physics can be understood within a field-theoretic framework.[1] Unfortunately, however, clear-cut experimental tests of the specific predictions of these theories are still lacking. In this Letter, we will present the results of a thorough and model-independent analysis of the problem of precocious scaling in field theories. Our predictions probe the detailed structure of the underlying field theory and reveal remarkable consistency with an experiment.

We studied the onset of scaling in the framework of the Wilson operator product expansion[2] (OPE)