Search for Forward Production of Massive States Which Decay with Muon Emission*†

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In a search for charmed particles the reactions $\pi^- + p \rightarrow p_r + \mu + X$ and $p + p \rightarrow p_r + \mu + X$ have been studied at beam energies of 200 and 240 GeV, respectively. Measurements of the beam particle and the slow recoil proton, p_r, were used to reconstruct the mass (M) of the $\mu + X$ system. Model-dependent upper limits, sensitive to threshold behavior, are presented for the forward production cross section times the muon branching ratio for high-mass states ($6 < M^2 < 54$ GeV^2).

This Letter reports the results of a charm search experiment which measured the reactions

$$\pi^- + p \rightarrow p_r + Y, \quad Y \rightarrow \mu + X, \tag{1}$$

and

$$p + p \rightarrow p_r + Y, \quad Y \rightarrow \mu + X, \tag{2}$$

where X represents anything. Data on Reactions (1) and (2) were taken at beam momenta (P_B) of 200 and 240 GeV, respectively. The beam particle, the recoil proton, p_r, and the muon were measured. From the beam and proton measurements the mass (M) of Y was determined.

The object Y may be any massive system which contains particles which decay into at least one prompt muon $+X$. Y may contain unusual objects such as charmed-particle pairs, heavy-lepton pairs, singly produced heavy bosons or baryons, and/or just "normal particles" such as π, K, etc. The latter provide background. The unusual particles give rise to muons only above the kinematic minimum value of M. The experimental technique used is particularly sensitive to states Y which are resonances or which result from the diffractive excitation of the beam particle.[1] For diffractive production, the M spectrum is expected to rise rapidly near the kinematic threshold and then fall as an inverse power of M.[2] This experiment was primarily motivated by the expectation that there may exist a strong threshold enhancement in the M spectrum due to the production of charmed particles.

For calibration purposes data on the reactions

$$\pi^- + p \rightarrow p_r + X \tag{3}$$

and

$$p + p \rightarrow p_r + X \tag{4}$$

were taken simultaneously with the data from Reactions (1) and (2). Other reactions studied simultaneously have been reported elsewhere.[3]

The apparatus for this experiment is shown in Fig. 1. It consists of beam-defining counters (not shown), a 63-cm-long hydrogen target, a spectrometer which measured the recoil proton, and a magnetized iron spectrometer which measured forward muons. The recoil spectrometer[4] consisted of a thin proportional chamber (PC1), four magnetostrictive wire spark chambers (SC1 to SC4), and five identical scintillator modules which subdivided the vertical aperture. Each module consisted of a 1.27-cm-thick scintillation counter (dE) to measure proton dE/dx and time of flight, a 29.0-cm-deep plastic scintillation

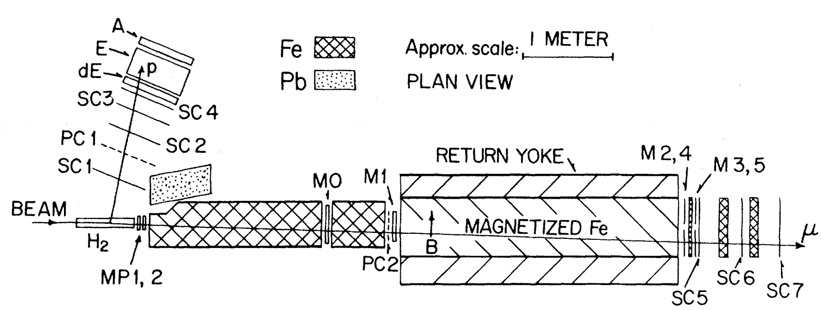

FIG. 1. The proton and muon detectors. For details, see text.

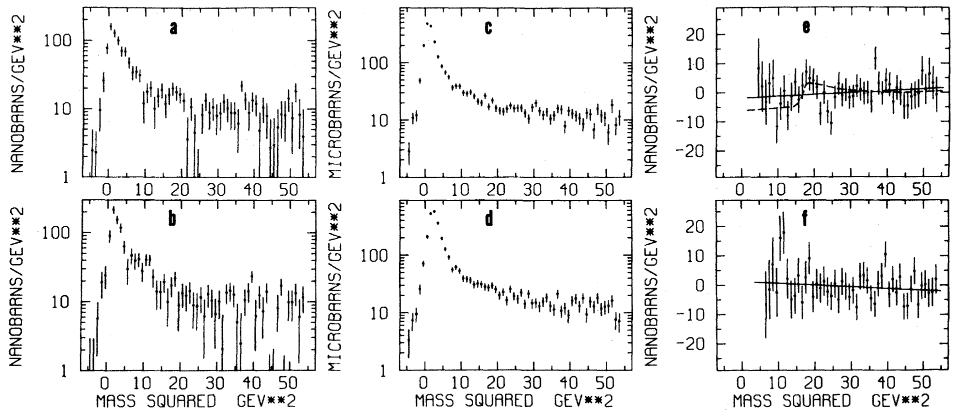

FIG. 2. (a), (b) $A_\mu B_\mu d\sigma_I/dM^2$ vs M^2 for Reactions (1) and (2), respectively, where A_μ is the muon acceptance, B_μ is the branching ratio $(Y \to \mu X)$, M is the mass of Y, and $d\sigma_I/dM^2 = \int (d\sigma/dM^2 dt)dt$ over the interval $0.1 < -t < 0.4$ GeV^2. (c), (d) $d\sigma_I/dM^2$ for Reactions (3) and (4), respectively. (e), (f) $A_\mu B_\mu d\sigma_I/dM^2$ for Reactions (1) and (2) with continuum background subtracted. Solid and dashed lines and additional details are described in text.

counter (E) to stop the proton and measure its energy, and an anticoincidence counter (A) to veto particles which did not stop. From the measurements of the beam and recoil-proton kinematic variables M^2 was measured to an accuracy of 2 GeV^2 (full width at half-maximum) with good mass acceptance for $0 < M^2 < 54$ GeV^2. The t acceptance was $0.1 < -t < 0.4$ GeV^2, where t is the square of the four-momentum transferred to the proton.

The muon spectrometer[3] consisted of a 244-cm-long nonmagnetized iron hadron absorber (starting 54 cm from the H_2 target center) followed by a $305 \times 54 \times 54$-cm^3 (useful volume) solid iron 18-kG magnet which bent the muons vertically. The counters M0 to M5 were used to identify a penetrating muon. The muon trajectories were determined by three magnetostrictive wire spark chambers (SC5 to SC7) at the rear of the magnet, and a multiwire proportional chamber (PC2) between the magnet and the hadron absorber. The muon transverse momentum, $P_{\perp\mu}$, was measured to ± 0.2 GeV, and its longitudinal momentum, $P_{L\mu}$, was measured to $\pm 16\%$ (rms). The kinematic acceptance limits of the muon spectrometer were $P_{L\mu} > 18$ GeV and $P_{\perp\mu}/P_{L\mu} \lesssim 0.05$.

Monte Carlo studies show that the muon acceptance (A_μ) is well parametrized by

$$A_\mu \simeq 1 - (M/P_B)(5.6 E_{\mu\,\mathrm{c.m.}}{}^{1/2} + 9/E_{\mu\,\mathrm{c.m.}}) \qquad (5)$$

for isotropic production of muons in the center of mass of the forward system (Y). $E_{\mu\,\mathrm{c.m.}}$ is the energy (GeV) of the muon in this system. The functional dependence of A_μ on other variables is weak.

A coincidence between a beam particle, a recoil proton, and a forward muon was required for an event to be recorded. In the analysis, accepted events satisfied the following criteria: only one beam particle; good tracks in the proton and muon spectrometers; vertex agreement between the proton, muon, and beam-particle trajectories; and identification of the recoil proton from the E and dE/dx measurements. (The vertex agreement did not limit the μ source to the H_2 target.) The M^2 spectra for events which met these requirements are shown in Figs. 2(a) and 2(b) for Reactions (1) and (2), respectively. These spectra have been corrected for the recoil-proton acceptance.[4] The vertical axis is $A_\mu B_\mu d\sigma_I/dM^2$ where $A_\mu B_\mu$ is the muon acceptance [Eq. (5)] times the branching ratio into muons $(Y \to \mu + Y)$ and σ_I is the cross section integrated over the interval $0.1 < -t < 0.4$ GeV^2. For comparison, the spectra of the corresponding calibration data ($d\sigma_I/dM^2$, no muon required) taken from Reactions (3) and (4) are shown in Figs. 2(c) and 2(d).

Qualitatively, the shapes of the spectra in Figs. 2(a) and 2(b) are similar to those of 2(c) and 2(d), respectively. The relative magnitudes of the cross sections ($\approx 10^{-3}$) are consistent with in-flight π and K decay. This indicates that there are no major structures indeed in the mass spectra as a result of the muon requirement. In order to quantify these comparisons, the "raw" calibration data (not corrected for the proton acceptance) were fitted with functions of the form

$$dN/dM^2 = a + bM^2 + c/M^{2n}, \qquad (6)$$

where a, b, c, and n were free parameters in the fits. Good fits were obtained separately for the data from Reactions (3) and (4) in the interval $4 < M^2 < 54$ GeV^2. These two functions were used as first-order estimates of the shape of the continuum and the background (e.g., π, K in-flight decay) in the data from Reactions (1) and (2). The two functions were normalized to the corresponding "raw" muon data yields in the intervals $4 < M^2 < 54$ GeV^2 for the data from Reaction (1), and $6 < M^2 < 54$ GeV^2 for Reaction (2). The normalized functions were then subtracted from the "raw" muon data and proton acceptance corrections were made. The resulting spectra, data of Reaction (1) [(2)] minus the normalized yield of Reaction (3) [(4)], are shown in Figs. 2(e) and 2(f). These subtraction spectra have been fitted by straight lines [solid lines on Figs. 2(e) and 2(f)]. The resulting χ^2's were 49 for 48 degrees of freedom (D.F.) for the data from Reaction (1) [Fig. 2(e)], and 45 for 46 D.F. for the data from Reaction (2) [Fig. 2(f)]. *Therefore, there are no statistically significant structures in these spectra.*[5]

In order to extract upper limits on $A_\mu B_\mu \sigma_I$ for "unusual"-particle production a number of models of expected line shapes were fitted to the spectra of Figs. 2(e) and 2(f). Our motivation in this experiment was to search for charmed-particle associated production for which we expect a threshold enhancement[2] due to either diffractive or resonant production. In general, the line shapes were assumed to be the sum of an enhancement at various masses, plus a linear background term, both folded with the mass resolution of the apparatus. To test for diffractivelike production we fitted the mass spectrum with a function in which $d\sigma/dM^2 = 0$ below threshold mass, M_T, and $d\sigma/dM^2 \propto 1/(M^2)^n$ above M_T.[6,2] The power n was taken from fits to the calibration spectra [Figs. 2(c) and 2(d)] with the form of Eq. (6) ($n_\pi = 1.62$ in the pion data and $n_p = 2.0$ in the proton data). To test for nondiffractive production,[2] n was set to equal to zero ($d\sigma/dM^2 \approx$ const).[7] These fits also set upper limits on other unusual reactions such as the production of heavy-lepton pairs.

If Y is a single object a resonance peak would be expected (e.g., associated charmed particles might be produced in a resonant state). To test for such narrower enhancements, a relativistic Breit-Wigner form with widths varying from $\Gamma = 50$ MeV (below the resolution limit) to 800 MeV was used.

The upper limits (2 standard deviations) on $A_\mu B_\mu \sigma_I$ which were obtained from these fits are shown in Table I. In order to extract a total-cross-section limit, σ_{tot}, from this table, further specific hypotheses describing the production and decay of "unusual" particles are necessary. For example, consider the case of inclusive, diffractive, charmed-meson pair production from Reaction (1) for which there are several specific effects which must be taken into account: (i) Either member of the pair (1 or 2) can decay by muon emission. Thus, for small branching ratios, the measured quantity in this experiment is $A_\mu \sigma_I (B_{\mu 1} + B_{\mu 2}) \equiv A_\mu \sigma_I \times 2\langle B_\mu \rangle$. (ii) For three-body decays (e.g., $K\mu\nu$), for a charmed-meson mass of 2 GeV ($M_{\text{pair}}{}^2 = 16$ GeV^2), the average center-of-mass energy of the muon would be ≈ 0.5 GeV, and from Eq. (5), $A_\mu \approx 0.56$. (iii) In order to estimate the total cross section we must assume the t dependence of the cross section. We take this to be the same as in Reaction (3) ($d\sigma/dt \propto e^{-bt}$, $b \approx 5$ GeV^{-2}) in which case 50% of the production occurs in the observed interval $0.1 < -t < 0.4$ GeV^2. Therefore the limit in Table I, $A_\mu B_\mu \sigma_I \approx 210$ nb, must be multiplied by a factor of 1.8 to obtain a limit on the diffractive cross section times the

TABLE I. 2-standard-deviation upper limits on $A_\mu B_\mu \sigma_I$ in nanobarns.

$M_T{}^2$ (GeV^2)	Threshold behavior[a] Diffractive, $n = 1.62$	Diffractive, $n = 2.0$	Nondiffractive, $n = 0$
	Pion beam		
6	90	...	3400
16	210	...	1400
35	510	...	1600
48	740	...	1800
	Proton beam		
9	...	190	3700
17	...	130	1900
37	...	430	2700
49	...	390	1900
	Breit-Wigner behavior[b]		
$M_R{}^2$ (GeV^2)	$\Gamma = 0.05$ GeV	$\Gamma = 0.2$ GeV	$\Gamma = 0.8$ GeV
	Pion beam		
7	31	43	85
18	32	62	97
37	37	54	116
50	39	58	188
	Proton beam		
11	73	92	161
18	35	44	79
39	42	57	115
50	25	44	157

[a] $d\sigma/dM^2 \propto (1/M^2)^n$ for $M > M_T$, 0 for $M < M_T$.
[b] $d\sigma/dM^2 \propto 1/[(M^2 - M_R{}^2)^2 + \Gamma^2 M_R{}^2]$.

average branching ratio of charmed mesons into muons. This limit is shown as a dashed curve on Fig. 2(e). The 2-standard-deviation limit on the inclusive charmed-meson diffractive pair-production cross section times the average branching ratio is then $\sigma_{tot}\langle B_\mu\rangle = 380$ nb. The corresponding total cross section for $K\bar{K}$ diffractive production is approximately 0.5 mb.[8] With the above assumptions, the ratio of the charmed and strange total diffractive cross sections is $\sigma(D\bar{D})\langle B_\mu\rangle/\sigma(K\bar{K}) < 10^{-3}$.

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[1]For examples of threshold enhancements at lower beam energies in $\pi + p$ see C. Caso *et al.*, Nuovo Cimento 54A, 983 (1968), for the πp threshold; J. Bartach *et al.*, Nucl. Phys. B7, 345 (1968), for πf; G. Otter *et al.*, Nucl. Phys. B96, 365 (1975), for πK^+K^-; B. D. Hyams *et al.*, Nucl. Phys. B22, 189 (1970), for K^+K^-; and G. Grayer *et al.*, Phys. Lett. 39B, 563 (1972), for $\bar{p}p$.

[2]F. C. Winkelmann *et al.*, Phys. Rev. Lett. 32, 121 (1974), and M. Jacob *et al.*, Phys. Rev. D 6, 2444 (1972), discuss diffractive production.

[3]G. J. Blanar *et al.*, Phys. Rev. Lett. 35, 346 (1975), and SLAC Report No. 191 (unpublished), and in *Proceedings of the International Symposium on Lepton and Photon Interactions at High Energies, Stanford, California, 1975,* edited by W. T. Kirk (Stanford Linear Accelerator Center, Stanford, Calif., 1975), and in *Particles and Fields, 1975,* edited by H. Lubatti and P. M. Mockett (Univ. of Washington, Seattle, Wash., 1975).

[4]D. Bowen *et al.*, Phys. Rev. Lett. 26, 1663 (1971).

[5]Cuts on $P_{\perp\mu}$, $P_{L\mu}$, and the forward charged-particle multiplicity, as measured in the detectors MP1,2 (Fig. 1) do not affect this result.

[6]Resolution limitations make the exact behavior at threshold inconsequential here.

[7]For $M^4 \le -t(2P_B)^2$ (the kinematic limit on M^4).

[8]The diffractive ($M^2 < 7$) cross section for $\pi^- + p \to p + K_S +$ anything at 205 GeV is 0.25 ± 0.13 mb (F. C. Winkelmann, private communication). From this we estimate that the diffractive strange-meson pair inclusive cross section is about 0.50 ± 0.25 mb.

Perhaps a Stable Dihyperon*

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In the quark bag model, the same gluon-exchange forces which make the proton lighter than the $\Delta(1236)$ bind six quarks to form a stable, flavor-singlet (with strangeness of -2) $J^P = 0^+$ dihyperon (H) at 2150 MeV. Another isosinglet dihyperon (H^*) with $J^P = 1^+$ at 2335 MeV should appear as a bump in $\Lambda\Lambda$ invariant-mass plots. Production and decay systematics of the H are discussed.

The possibility that hadrons may be described by a confined color gauge theory of quarks and gluons has attracted great interest recently.[1] The bag model[2,3] provides an adaptation of these ideas to conventional spectroscopy. The S-wave baryons (Q^3) and many features of the S-wave mesons ($Q\bar{Q}$) are remarkably well described by the model in terms of four parameters of relatively fundamental significance.[3] Furthermore, the model may be applied to any S-wave color-singlet multiquark system ($Q^m\bar{Q}^n$, for $n+m>3$) without additional parameters. It offers the hope of answering long-standing questions regarding the nature and experimental elusiveness of the exotics.[4,5]

Here I wish to point out that the same model applied to the Q^6 system predicts the existence of certain relatively light dihyperons, one of which may be stable. Specifically, the model predicts an S-wave flavor-singlet dihyperon (H) with $J^P = 0^+$ at 2150 MeV. With this mass, the H must