Search for Charmed Hadrons Using a Direct-Muon Trigger*

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We present cross-section upper limits for the production of narrow states produced in 15.5-GeV π^+N collisions, in coincidence with single muons. These limits are derived from an invariant-mass search involving all charged-hadron tracks in the final state, as observed in a large streamer chamber. We also give upper limits for the production of muon-associated Λ^0 and K^0 particles.

In this Letter we report on an experiment searching for long-lived heavy hadrons emerging from π^+N collisions, preferentially in conjunction with a "prompt" muon. The existence of such particles could be interpreted in terms of a new hadronic quantum number called charm, as postulated in 1964¹ on the grounds of lepton-hadron symmetry. This concept was later used² in a gauge theory to cancel the $\Delta S \neq 0$ neutral current in order to explain the observed very small K_L^0 - K_S^0 mass difference and the small decay width for $K_L^0 \rightarrow \mu\mu$. The discovery, in high-energy neutrino interactions, of the $\Delta S = 0$ weak neutral current,³ as well as the observation of "direct" lepton signals in hadron-hadron collisions,⁴ made the existence of charm plausible, and motivated this experiment.⁵

Adopting the most straightforward tenets of charm phenomenology, we assumed that particles carrying the new quantum number are produced in pairs in a strong interaction ("associated production") with lifetimes $\tau \leq 10^{-13}$ sec and accordingly narrow widths. They decay either (semi-) leptonically or hadronically, and may yield a predominance of events containing strange particles among the resulting hadrons.

These features made a charm search a logical sequel to the μ - N inelastic scattering experiments we recently completed,⁶ using a 2-m streamer chamber at the Stanford Linear Accelerator Center (SLAC). This experiment featured a μ trigger, nearly 4π acceptance for final-state hadrons, and good mass resolution ($\Delta M/M \sim 1\%$). For the charm search, the μ beam was changed to a 15.5-GeV π^+ beam. The reaction is then assumed to proceed according to the scheme

$$\begin{aligned} \pi^+ p &\rightarrow c_1 \bar{c}_2 + \dots \\ &\quad \downarrow \\ &\quad \mu \nu + \dots \text{ (or } \rightarrow \text{ hadrons)} \\ &\quad \downarrow \\ &\quad \text{hadrons (or } \rightarrow \mu \nu + \dots). \end{aligned} \quad (1)$$

c_1 and $\bar{c}_2$ (which can be mesonic or baryonic $c \neq 0$ states) are estimated to have masses which make their production possible at our center-of-mass energy $\sqrt{s} \sim 5.6$ GeV. One decay provides the triggering muon, the other the hadrons which, if charged, permit reconstruction of invariant masses. The assumed lifetime implies total decay widths below our measurement accuracy. Figure 1 shows the experimental apparatus: The 2-m streamer chamber in a 16-kG magnetic field contains 16 polyethylene target blocks, each $2.0 \times 1.5 \times 0.6$ cm³, spaced 7 cm apart along the beam trajectory. Approximately 2 m downstream from the chamber, a 1.5-m-thick lead wall acted as a hadron absorber and, together with four scintillation hodoscopes, as a muon identifier. To reduce the dominant trigger, muons originating from meson decay, the space between chamber and lead shield was filled with polyethylene wherever possible. The resulting trigger enhances the prompt-muon-associated events by approximately two orders of magnitude over untriggered experiments.

A total of 12 000 pictures were taken with the muon trigger from a total of 15.5×10^6 π interactions in a 1-week run. All events were then scanned, measured, and processed with a spe-

FIG. 1. Experimental apparatus showing 2-m streamer chamber in a 16-kG magnetic field. Trigger hodoscopes and hadron absorber are arranged on both sides of beam line and pulsing system.

FIG. 2. (a) Invariant mass distribution for two positive plus two negative tracks, *assuming* all tracks are due to pions. (b) Invariant mass distribution of measured vees, assuming both tracks are due to pions. The ensuing K^0 mass peak has a width of $7 \text{ MeV}/c^2$ (full width at half-maximum).

cial streamer-chamber version of the reconstruction programs TVGP and SQUAW. The triggering μ track was identified from on-line computer information. All other tracks originating at the interaction vertex (as well as vees from K^0 or Λ^0 decays) were then used in a general search for narrow peaks.

Over 350 different mass combinations (two body to six body, including exotics) were looked at, independent of *any* model assumption. All muon candidates, which are clearly identified by tracking through the absorber, are eliminated from the mass search; this reduces the combinatorial background considerably. A typical plot is shown in Fig. 2(a) and the K^0 mass distribution is shown in Fig. 2(b).

In the mass plots, the background levels are increased by combinatorial effects inherent in our search for invariant-mass peaks. Combinatorial effects are aggravated by the lack of particle identification. Also, no kinematical fitting was attempted to eliminate events that contain multiple neutrals from our sample. However, any state with width less than our resolution and a sufficient production cross section will stand out above these backgrounds.

We reduce the combinatorial backgrounds by

FIG. 3. Trigger efficiencies due to muon detection, for given muon momentum, plotted versus transverse momentum.

assuming that only *one* pair of charmed hadrons was produced per event, and that only one of the pair decayed hadronically to charged particles. This implies that there can be at most one charmed entry in any mass interval from a single event for a given n -particle combination. Thus all plots were "masked" in such a way that no histogram bin contained more than one entry per event.

Using the known π^+N total cross section at $15.5 \text{ GeV}/c$, the experimental sensitivity for charmed-particle production was determined to be $1/627 B_L B_H \eta \mu\text{b/event}$, where B_L and B_H are the branching ratios into muonic and charged hadronic modes, respectively, and η is the detection efficiency for the muon. It is a strong function of the unknown charm production and decay distributions, mainly in transverse momentum ($p_\perp$) and energy (E) of the muon. This detection efficiency for the muon is shown in Fig. 3.

The results of the mass search are displayed in Table I. Invariant-mass distributions for two-, three-, four-, and five-charged-particle systems were computed using *assumed* $\pi^\pm$, $K^\pm$, and $p^\pm$ mass hypotheses. Table I lists, for each particle combination and for three mass ranges, the 97%-confidence upper limits to the cross sections for charmed-particle production, assuming a simple model for transverse momentum $p_\perp$ and energy E of the c -decay muon. These upper limits were determined by scanning each mass region, in bins consistent with our mass resolution, for the bin that maximized the quantity $N_{\text{total}} - N_{\text{background}} + 2(N_{\text{total}})^{1/2}$.

We have looked at a total of some 70 000 mass combination bins. To evaluate the statistical significance of any one-bin peak in the effective-

TABLE I. Range of upper limits for production of narrow hadronic states decaying into any charge combination of the particles indicated, excluding neutral pions and neutrons. Values quoted are in microbarns, and refer to the lowest and highest upper-limit values for each channel. This table summarizes the information on some 350 charge and mass combinations, computed for three invariant-mass ranges: threshold to $1.5 \text{ GeV}/c^2$; 1.5 to $2.4 \text{ GeV}/c^2$; 2.4 to $3.1 \text{ GeV}/c^2$. A more detailed table can be obtained from the authors on request.

$K\pi$	0.5–12	$\Lambda\pi$	1–3
$K\pi\pi$	0.5–10	$\Lambda\pi\pi$	1–3
$K\pi\pi\pi$	1–12	$\Lambda\pi\pi\pi$	1–4
$K\pi\pi\pi\pi$	1–7	Λp	4–5
$KK\pi$	1–13	$\Lambda\bar{p}$	<2
$KK\pi\pi$	1–12	$p\bar{p}$	5–8
$KK\pi\pi\pi$	2–10	$p\bar{p}\pi$	2–8
KK	0.5–10	$\bar{p}\bar{p}$	2–3
KKK	1–11	$\bar{p}\pi$	1–9
$KKKK$	2–8	$\bar{p}\pi\pi$	1–9
ΛK	1–4	$p\bar{p}\pi$	3–15
$\Lambda K\pi$	1–4	$p\bar{p}\pi\pi$	3–7
$\Lambda K\pi\pi$	1–4	pK	3–15
$p\pi$	2–13	$pK\pi$	4–14
$p\pi\pi$	2–12	$pK\pi\pi$	5–13
$p\pi\pi\pi$	2–7	$\bar{p}K$	1–6
$p\pi\pi\pi\pi$	2–7	$\bar{p}K\pi$	2–14
$\pi\pi$	0.5–9		
$\pi\pi\pi$	0.5–7		
$\pi\pi\pi\pi$	1–7		
$\pi\pi\pi\pi\pi$	1–6		

mass distributions, we have used the mass data to define a background curve for each bin i by applying the procedure of running mean values over eleven bins from $i-5$ to $i+5$ with an effective constraint on the derivative.⁷ This procedure, which is questionable only in regions of steeply changing population (e.g., at the lower end of phase space), avoids most pitfalls of model building for the background. Its inherent inaccuracy close to threshold persuaded us not to use the first eight bins in any mass combination to set cross-section limits.

The sensitivity of the experiment given by $B_L \times B_H \sigma(c\bar{c})$ is $\sim 10 \text{ nb/event}$, using a muon detection efficiency of 0.16.⁸ To establish the 97%-confidence limits for the charm production cross sections $\sigma(c\bar{c}) = \sigma_{\text{meas}}/B_L B_H \eta$ of Table I, $B_L B_H \eta$ was estimated to be ~ 0.016 , using $B_L B_H = 0.1$.

Figure 4(a) shows the distribution of standard deviations from the smoothed background curve for a representative data sample. While we see no significant deviations from Poisson statistics, there are three bins with probability less than

FIG. 4. (a) Distribution of standard deviations from a smooth background, for the invariant mass plots. The inset shows the high-deviation tail on an expanded scale. (b) Invariant-mass plot for two oppositely charged tracks, assuming they are due to kaons, with a cut on the transverse momentum. Inset: expanded plot of region around $m(K^+K^-) \sim 2000 \text{ MeV}/c^2$. (c) Invariant-mass plot for one negative plus two positive tracks, assuming they are due to an antiproton and two π^+ .

one over the number of bins studied, i.e., $\leq 1.3 \times 10^{-5}$. They are located at $m(K^+K^-) = 1.244 \text{ GeV}/c^2$, $m(K^+K^-) = 1.984 \text{ GeV}/c^2$, and $m(\bar{p}\pi^+\pi^+) = 1.750 \text{ GeV}/c^2$. [Two of these are shown in Figs. 4(b) and 4(c).] The corresponding values for the production cross section with the assumed efficiencies and branching ratios are 2.3 ± 0.5 , 1.9 ± 0.4 , and $7.3 \pm 0.9 \mu\text{b}$, respectively. The quoted errors are statistical only. A detailed investigation of all events in these bins did not uncover any other telling feature such as additional strange-particle production. We feel that, because of its quantum numbers, the enhancement at $m(K^+K^-) = 1984 \text{ MeV}/c^2$ is the most promising one for further investigation.

We also use the inclusive K^0 and Λ^0 production observed in this experiment to set upper limits

on the cross sections:

$$\begin{aligned} \pi^+ N \rightarrow K^0 \mu + \dots \\ \rightarrow \Lambda^0 \mu + \dots, \quad p(\mu) \geq 2 \text{ GeV}/c. \end{aligned} \quad (2)$$

Note that, in the conventional charm scheme, a large fraction of associated charm production will yield these signatures [cf. relation (1)]. These upper limits are 10.0 and 2.0 μb , respectively.

While some sets of data are under additional scrutiny at this time, we see no conclusive evidence for muon-associated production of long-lived states decaying into two, three, four, or five charged hadrons at the microbarn level. We are currently starting an improved version of this experiment, which will give us a tenfold increase in statistics while, at the same time, improving the muon enrichment by a factor of 3.

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¹Y. Hara, Phys. Rev. **134**, B701 (1964); B. J. Björken and S. L. Glashow, Phys. Lett. **11**, 255 (1964).

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

³F. J. Hasert *et al.*, Phys. Lett. **46B**, 121, 138 (1973).

⁴J. P. Boymond *et al.*, Phys. Rev. Lett. **33**, 112 (1974);

J. A. Appel *et al.*, Phys. Rev. Lett. **33**, 722 (1974).

⁵S. L. Glashow, in *Experimental Meson Spectroscopy*, AIP Conference Proceedings No. 21, edited by D. Garelick (American Institute of Physics, New York, 1974), p. 387. We first discussed our approach at the Twelfth Course of the International School of Physics, Erice, 1974; C. A. Heusch, in *Lepton and Hadron Structure*, edited by A. Zichichi (Academic, New York, 1975).

⁶C. del Papa *et al.*, Phys. Rev. D **13**, 2934 (1976); also see R. Mozley, 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); C. A. Heusch, in *Proceedings of the Seventeenth International Conference on High Energy Physics, London, England, 1975*, edited by J. R. Smith (Rutherford High Energy Laboratory, Didcot, Berkshire, England, 1975).

⁷This procedure uses in part the smoothing package available with the SLAC plotting program KLOWA. [See Jerry Friedman and Roger Chaffee, SLAC Computation Group Technical Memorandum No. 146, 1973 (unpublished)].

⁸To estimate these quantities, we adopt standard assumptions as outlined in M. K. Gaillard, B. W. Lee, and J. L. Rosner, Rev. Mod. Phys. **47**, 277 (1975).

Transient Field of ^{19}F Ions Recoiling in Nickel Interpreted by a Spin-Dependent Molecular-Orbital Promotion Mechanism*

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Transient magnetic fields have been observed from a phase shift of the time-differential perturbed angular correlation of ^{19}F nuclei recoiling into a nickel host. The Larmor precession associated with the phase shift grossly exceeds the Lindhard and Winther prediction. A spin-dependent electron-promotion mechanism via molecular orbitals is suggested which results in an intermittent *K*-shell spin polarization.

The magnetic fields acting at the site of the nucleus of ions during a slowing-down process in polarized ferromagnetic foils (transient fields) are a subject of still growing interest. By adjust-

ing the Lindhard and Winther (LW) theory,¹ which describes the scattering of polarized electrons by the moving ion, it was possible to reproduce the *Z* dependence of the transient fields. Recently,