Search for $D^0(1865)$ Mesons Produced in Association with Prompt Muons in Hadronic Interactions

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We present the results of a search at Fermilab for the charmed meson, $D^0(1865)$, produced in association with a prompt muon by 300-GeV/c neutrons. We observe no significant enhancement in high-mass $K^\pm\pi^\mp$ systems and report, at the 95% confidence level, an upper limit of 200 nb/nucleon for the production of a pair of charmed particles and their subsequent decay into a $K^\pm\pi^\mp$ state and a prompt muon.

The recent observations of narrow states of several GeV mass in e^+e^- annihilation[1] and in photoproduction[2] have provided evidence for the electromagnetic production of charmed particles. However, there has been no direct evidence of charm production in hadronic interactions.[3] Presumably, at the level of sensitivity of these experiments, the small charm cross section was obscured by a large background. In order to improve the sensitivity of the search for charm in hadronic interactions the present experiment uses a selective trigger based on the following assumptions: (1) Charmed particles must be produced in pairs in hadronic collisions.[4] (2) The branching ratio for the semileptonic decay of a charmed particle into electrons or muons is substantial (~15%).[5] (3) The average longitudinal and transverse momenta of the decay lepton are very modest at Fermilab energies:

$$\langle p_L \rangle \sim 5\text{–}10 \text{ GeV}/c,$$

$$\langle p_T \rangle \sim 0.2\text{–}0.5 \text{ GeV}/c.$$

(4) A $\Delta C = \Delta Q$ rule should apply for charm decay (e.g., $D^0 \to K^-\mu^+\nu$ is allowed while $D^0 \to K^+\mu^-\bar{\nu}$ is forbidden).[4] Specifically, the detection scheme requires one member of the charmed pair to decay semimuonically, providing a prompt muon for the trigger; the $K^\pm\pi^\mp$ decay of the associated particle is then detected using a large-aperture spectrometer.

The experiment was performed at the Fermi National Accelerator Laboratory in the 1-mrad M-3 neutral beam. During typical running conditions, 1.5×10^6 neutrons per pulse, having an average momentum of 300 GeV/c, were incident on a 5%-absorption-length beryllium target. Contamination of neutron-induced data from photon and $K_L{}^0$ sources was negligible.[6] To determine the absolute normalization, the neutron flux was monitored continuously using a calorimeter placed in the beam.

The detector, shown in Fig. 1, consisted of a two-arm spectrometer; the upward muon-defining arm provided the trigger for the experiment, and the forward large-acceptance arm was used to detect the particles produced in association with the muon. Specifically, the muon arm was a hadron absorber composed of two absorption lengths of tungsten placed immediately downstream and slightly above the target, followed by 16 ft of iron, 6 ft of which were magnetized (the return yoke of a BM109 magnet). Interspersed in the iron were four hodoscopes ($M0$, $M1$, $M2$, $M3$) used for triggering, and eighteen spark-chamber gaps which provided momentum and angle infor-

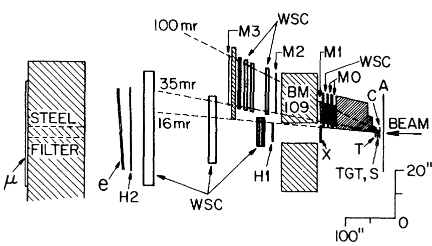

FIG. 1. Schematic of the apparatus (elevation view). Trigger muons were identified in the upper arm, 35 $\leq \Theta \leq$ 100 mrad. Associated particles were detected in the forward arm, $\Theta \leq$ 16 mrad.

mation for the muon. The acceptance of this arm was ±100 mrad horizontally, and from 35 to 100 mrad vertically. The magnet yoke provided a transverse momentum impulse of roughly 0.75 GeV/c. Multiple scattering limited momentum resolution to about ±25%. The momentum acceptance for muons was $6.5 < p < 50$ GeV/c and $0.2 < p_T < 1.2$ GeV/c.[7] The muon arm was shielded from off-axis, beam-associated muons by a large scintillation counter array (A) placed upstream of the beryllium target (TGT).

The forward arm of the detector was a conventional counter, wire-spark-chamber spectrometer. A scintillation counter (C), just upstream of the target, was used to veto events generated by charged beam particles. Immediately downstream of the target were a trigger counter (S), in which a positive signal indicated a target interaction, and a 24-element vertex hodoscope (T). Although T was not required in triggering, off-line analysis of the pulse-height distribution recorded by the 0.8-mm-wide×16-mm-high scintillation elements determined the interaction vertex in the magnet bend plane to within ±0.5 mm.

The angular acceptance of the forward arm was limited to ±60 mrad horizontally and from −20 to to +16 mrad vertically. Particles passing through the magnet aperture received an impulse of 1 GeV/c in transverse momentum. Charged particles emerging downstream of the magnet were detected by the $H1$ hodoscope and their trajectories were measured using twenty planes of wire spark chambers. Particles having momenta $P_{\mathrm{lab}} > 10$ GeV/c were accepted and the resolution (σ) of the momentum measurement was $\delta p/p < 1\%$.

The forward arm was equipped with additional detectors for lepton identification (electrons as well as muons using arrays $X, H2, e, \mu$). The analysis of events with forward-produced leptons is described in the following Letter.

An interaction in the target, induced by a neutral beam particle, in conjunction with at least one minimum-ionizing pulse in each of the muon hodoscopes, and a coincident signal in the forward arm downstream of the magnet was required to satisfy the trigger:

$$\text{trigger} = (\bar{C} \cdot S) \cdot (\bar{A} \cdot M0 \cdot M1 \cdot M2 \cdot M3) \cdot H1 .$$

Roughly one in 2×10^4 interactions satisfied the above trigger requirement. A total of 2.6×10^5 triggers were recorded in a four-week running period. About 50% of the raw triggers yielded acceptable reconstructed muons in the off-line analysis (i.e., muons which were tracked through the entire set of chambers in the upper arm).

Events in the forward spectrometer were analyzed using a pattern recognition program capable of reconstructing events having a charged-particle multiplicity of ≲10 tracks downstream of the magnet. Multiple-track efficiency was ≳95% due to the large redundancy of planes. The average multiplicity of charged tracks observed downstream of the magnet was found to be about 4 (this is ~30% of the average charge multiplicity produced in a typical n-Be interaction at 300 GeV/c).

Since no particle identification was available in the hadron arm, the invariant mass of a given multibody combination was calculated using all possible mass assignments.[6] Figure 2 displays $K^{\pm}\pi^{\mp}$ invariant-mass distributions associated with a given muon trigger ($\mu^{\pm}$) in bins comparable to the mass resolution (~20 MeV/c^2). (Correction for acceptance, which is slowly varying as a function of mass, is not included.) The events in Fig. 2 satisfy the requirement that the fraction of the momentum carried away by either particle $[R = P_+/(P_+ + P_-)]$ must lie between 0.25 and 0.75 of the momentum of the $K\pi$ pair. The variable R enters into the formula for invariant mass in the following way:

$$M^2 \approx P_+P_-\theta^2 + M_+^2/R + M_-^2/(1-R) ,$$

where $P_{\pm}$ are the laboratory momenta of the two decay products of M, θ is their relative opening angle, and $M_{\pm}$ are assigned rest masses. The

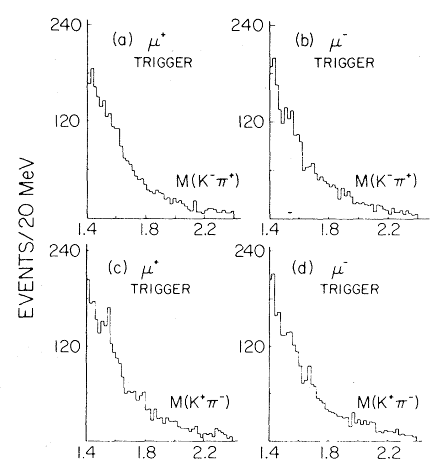

FIG. 2. $K\pi$ mass combinations associated with a muon trigger. The constraint $0.25 \leq R \leq 0.75$ has been imposed. According to standard phenomenology, only data in (b) and (c) should contain D^0 production signals. The mass scales are in GeV/c^2.

reason for this R cut is that hadronic background at large $K\pi$ mass values is derived mainly from events where the K and π have a large rapidity difference; that is, the K and π differ considerably in longitudinal momentum. However, a low-spin object such as the $D^0(1865)$ meson would tend to decay isotropically in its helicity frame. Hence the cut $0.25 \leq R \leq 0.75$ eliminates roughly half of a potential D^0 signal[8]; the same cut, on the other hand, removes nearly 90% of the high-mass hadronic background, which is confined mainly to either large or small values of R.

No significant signal is observed in any of the two-body mass distribution displayed in Fig. 2. Had a significant signal been observed, however, a correlation between the sign of the trigger muon and the sign of the kaon in the two-body system could have been used to verify a possible $\Delta C = \Delta Q$ rule. For example, if charmed-pair production and subsequent decay were to follow the usual scheme,[4] we would expect to see peaks only in the plots 2(b) and 2(c). Although the lack of any narrow enhancements obviates such a test, the muon sign correlation can be used to reduce the yield of background events by a factor of 2 in any distribution, thereby increasing the sensitivity of our estimated upper limits for charm production.

In order to determine a cross-section upper limit for charm production by hadrons, we have combined the data of Figs. 2(b) and 2(c). By Monte Carlo techniques we have estimated an acceptance of 1.5% in the upper arm for a muon from charm decay and an acceptance of 10% in the forward arm for $K\pi$ pairs from D^0 or $\bar{D}^0$ decay.[9] Further, we have assumed that to detect a D^0 signal, we would have to observe at least a 2-standard-deviation peak above background in a 20-MeV/c^2 mass interval at a $K\pi$ mass of 1860 MeV/c^2. Thus, at the 95% confidence level, we obtain

$$\sigma_{DC} B_1 B_2 < 200 \text{ nb/ nucleon},$$

where σ_{DC} is the cross section for production of either a D^0 or $\bar{D}^0$ meson in association with another charmed particle C; B_1 is the branching ratio for the semimuonic decay of C; B_2 is the branching ratio of neutral D mesons into $K\pi$ pairs ($D^0 \to K^-\pi^+$, $\bar{D}^0 \to K^+\pi^-$). Assuming the values $B_1 = 15\%$ and $B_2 = 3\%$, we obtain an upper limit for σ_{DC} of

$$\sigma_{DC} < 44\ \mu\text{b/nucleon (95\% confidence level)}.$$

[In converting cross sections from Be to a nucleon target, we have divided the observed results by the effective number of nucleons: $A_{\text{eff}}(\text{Be}) = 6.4$.]

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1G. Goldhaber *et al.*, Phys. Rev. Lett. 37, 255 (1976); I. Peruzzi *et al.*, Phys. Rev. Lett. 37, 569 (1976).

2B. Knapp *et al.*, Phys. Rev. Lett. 37, 882 (1976).

3M. A. Abolins *et al.*, Phys. Rev. Lett. 37, 417 (1976); D. Bintinger *et al.*, Phys. Rev. Lett. 37, 732 (1976); J. C. Alder *et al.*, Phys. Lett. 66B, 401 (1977); G. Coremans-Bertrand *et al.*, Phys. Lett. 65B, 480 (1976); V. Cook *et al.*, Phys. Lett. 64B, 221 (1976); K. C. Stanfield, BNL Report No. BNL 50598, 1976 (unpublished); E. Bleser *et al.*, Phys. Rev. Lett. 35, 76 (1975).

4M. K. Gaillard, B. W. Lee, and J. Rosner, Rev. Mod. Phys. 47, 277 (1975).

5Recent unpublished results from DORIS suggest that the semileptonic branching ratio for charmed particles is ~15%.

6For further discussion see Bleser *et al.*, Ref. 3.

7Distributions for particles in the muon arm were reported elsewhere. See R. C. Ruchti, in *Particle Searches and Discoveries—1976*, AIP Conference Proceedings No. 30, edited by R. S. Panvini (American Institute of Physics, New York, 1976).

8The R cut is essentially equivalent to restricting data to two-body decays with polar angles in the helicity frame between 45° and 135°.

9Monte Carlo calculations have shown that the acceptance in either arm is not very sensitive to reasonable variations in the parameters used to describe the x and p_T characteristics of charmed-particle production. (We have assumed the forms e^{-5x} and $e^{-1.5 p_T^2}$ hold for all charmed particles, since the lowest-lying states, for both mesons and baryons, have comparable masses and the actual production distributions are not known.) However, the acceptance in the upward arm for muons from the semileptonic decay of charmed states is very sensitive to the amount of hadronic mass accompanying the μ. Assuming that the process $D \to K^*(890)\mu\nu$ is representative of the average charmed-particle decay, we obtain a 1.5% acceptance for these muons. [For $D \to K\mu\nu$ the acceptance is 2.3%, while for $D \to K(1250)\mu\nu$ the acceptance is 0.7%.]