Production of the $D_s^{\pm}$ by High-Energy Neutrons

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We have observed the production of the $D_s^{\pm}$ by a high-energy neutron beam on nuclear targets. The $D_s^{\pm}$ was observed in the decay mode $D_s^{\pm} \to \phi\pi^{\pm}$, $\phi \to K^+K^-$. The average of the inclusive cross sections for D_s^+ and D_s^- hadroproduction is measured to be $B\,d\sigma/dx_F = 2.85 \pm 0.80 \pm 0.86$ μb/nucleon at $x_F = 0.175$ on the assumption of a linear A dependence, where $B \equiv \Gamma(D_s^{\pm} \to \phi\pi^{\pm})/\Gamma(D_s^{\pm} \to \text{all})$.

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We have measured the cross section times branching fraction for hadroproduction of the decay mode $D_s^{\pm} \to \phi\pi^{\pm}$. This mode has been previously observed[1] in e^+e^- annihilation to have a mass of $1970 \pm 5 \pm 5$ MeV/c^2 and has since been confirmed by several observations. Several experiments have measured the branching fraction for $D_s^{\pm} \to \phi\pi^{\pm}$, but the value is not yet well determined.[1-4] Previously published information on the hadroproduction of the D_s^+ has been severely statistics limited.[5,6] We have observed a 64-event $D_s^{\pm} \to \phi\pi^{\pm}$ signal at a mass of 1972 ± 5 MeV/c^2 produced by high-energy neutrons.

The experiment was performed in the Proton East beam line at Fermi National Accelerator Laboratory. The incident neutron beam was formed by 800-GeV protons incident on a beryllium target. The neutron energy spectrum ranged from 0 to 800 GeV and was triangular in shape, with a most probable energy at 640 GeV ($\sqrt{s}$ of 35 GeV). The contribution to the neutral beam from photons and K_L^0's above 200 GeV was negligible.

A layout of the apparatus and detailed description of the spectrometer have been given previously.[7] Briefly, the detector consists of an active target and vertex detector, a magnetic spectrometer, a gas Cherenkov system, and electromagnetic and hadronic calorimetry. The target was composed of three segments consisting of tungsten, silicon, and beryllium. The total event energy was obtained by summation of the output of the electromagnetic, hadronic, and beam dump calorimetry. The summed response of the electromagnetic and hadronic calorimeters was used as our minimum-energy trigger.

Charged-particle identification was accomplished with use of three 34-cell Cherenkov counters, operating (from upstream to downstream) with pion thresholds of 2.8, 10.8, and 5.7 GeV/c, respectively. Protons could be uniquely identified from 10 to 80 GeV/c, while unique kaon identification extended from 10 to 40 GeV/c.

The data for this analysis consisted of approximately 45×10^6 events. The event trigger required that all of the following conditions be satisfied: (a) a coincidence between a target-region scintillation counter and two coincidences in a downstream scintillator hodoscope; (b) a minimum calorimeter trigger energy of 265 GeV; (c) a minimum multiplicity of four charged tracks in the downstream spectrometer; (d) a deposited charge in the most downstream active silicon target equivalent to two or more charged tracks; (e) at least one charged kaon with momentum over 21 GeV/c or one proton over 40 GeV/c traversing the entire detector. All triggers satisfying requirements (a) through (e) were subject to a procedure which found all charged tracks and a common vertex, and which then performed a Cherenkov-counter analysis.

Figure 1 shows a K^+K^- invariant-mass distribution with a prominent ϕ signal. Each kaon candidate is required to be uniquely Cherenkov identified (i.e., unambiguous with either the pion or proton hypothesis). Because this state has a natural width comparable to our spectrometer resolution, we have performed the fit to the signal by the convolution of a Breit-Wigner shape of appropriate width[8] with a Gaussian distribution. The background has been fitted by a third-order polynomial. The result is 33000 candidates with a mass at 1019.5 MeV/c^2. We selected ϕ candidates by applying a K^+K^- mass cut of 1019.5 ± 3.5 MeV/c^2.

To perform the $D_s^{\pm}$ search, these ϕ candidates were combined with charged tracks, with the assumption of a

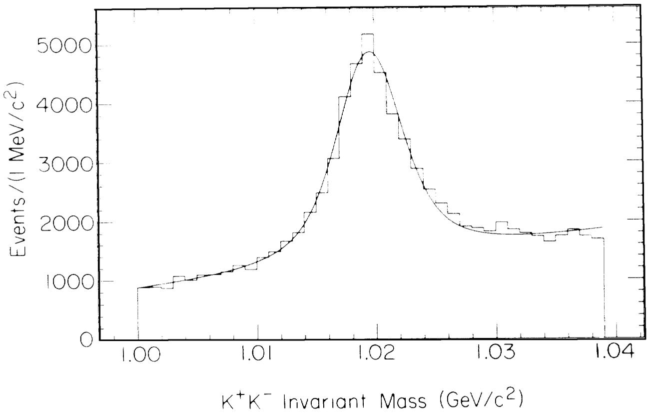

FIG. 1. K^+K^- mass spectrum.

pion mass. Those tracks positively identified as either a kaon or proton with information from the Cherenkov counters were excluded. The resulting $\phi\pi^{\pm}$ invariant-mass histogram is shown in Fig. 2. A multiplicity requirement of less than fourteen tracks has been applied to reduce the combinatoric background. This distribution has been fitted with a Gaussian peak representing $D_s^{\pm} \rightarrow \phi\pi^{\pm}$ decay over a smooth background. We have included an additional peak located near the known D^+ mass in order to represent the $D^{\pm} \rightarrow \phi\pi^{\pm}$ process. The widths of the $D_s^{\pm}$ and $D^{\pm}$ peaks were constrained to be identical. The fit gives 65 ± 29 $D_s^{\pm}$ candidates with a mass of 1981 ± 5 MeV/c^2 and a width of 8.5 ± 2.7 MeV/c^2, and also 69 ± 38 $D^{\pm}$ candidates with a mass of 1873 ± 8 MeV/c^2.

For the decay $D_s^+ \rightarrow \phi\pi^+$, the angle θ between the K^+ and the π^+, when viewed in the ϕ rest frame, is expected to follow the distribution given by $dN/d\cos\theta \propto \cos^2\theta$. The rather significant forward-backward peaking present in the $\cos\theta$ distribution can be exploited to improve the signal-to-background ratio in the $D_s^{\pm}$ search, because our spectrometer has flat acceptance in θ.

Figure 3 is a fit to the $\phi\pi^{\pm}$ invariant-mass histogram requiring that $|\cos\theta| \geq 0.5$. We observe 64 ± 16 $D_s^{\pm}$ events for a significance of 4.0 standard deviations. The mass is 1972 ± 5 MeV/c^2 and the width is 8.4 ± 3.5 MeV/c^2, which is consistent with our detector resolution for this state. The fit also gives 47 ± 23 $D^{\pm}$ events at the mass 1876 ± 4 MeV/c^2. Comparison of the data of Figs. 2 and 3 shows that $(98 \pm 37)\%$ of the $D_s^{\pm}$ signal and only 50% of the background survives the $\cos\theta$ cut. The survival fraction obtained in the data for the signal is consistent with the expected value of 87.5% obtained by integration of the $D_s^{\pm} \rightarrow \phi\pi^{\pm}$ angular decay distribution.

We have examined the possibility of a contribution to the narrow $\phi\pi^+$ mass peaks seen in Fig. 3 from kinematic reflections of misidentified charm states (e.g., $D^+ \rightarrow K^-\pi^+\pi^+$ or $\Lambda_c^+ \rightarrow pK^-\pi^+$). We compute the level of such contamination to be very low both because of the low level of Cherenkov misidentification as measured in topologically isolated $\Lambda \rightarrow p\pi^-$ and $K_S \rightarrow \pi^+\pi^-$ decays, and because of the tight requirement that the K^+K^- invariant mass lie within 3.5 MeV of the ϕ mass. Finally, kinematic reflections observed in our spectrometer would produce very broad enhancements in the $\phi\pi^{\pm}$ mass plot with widths exceeding 100 MeV. We conclude that reflections from other charm states cannot account for the D_s^+ or D^+ signals present in Fig. 3.

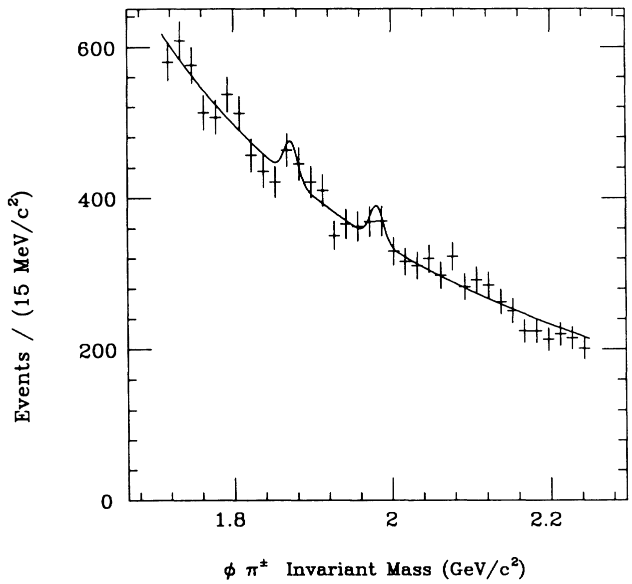

FIG. 2. $\phi\pi^{\pm}$ mass spectrum.

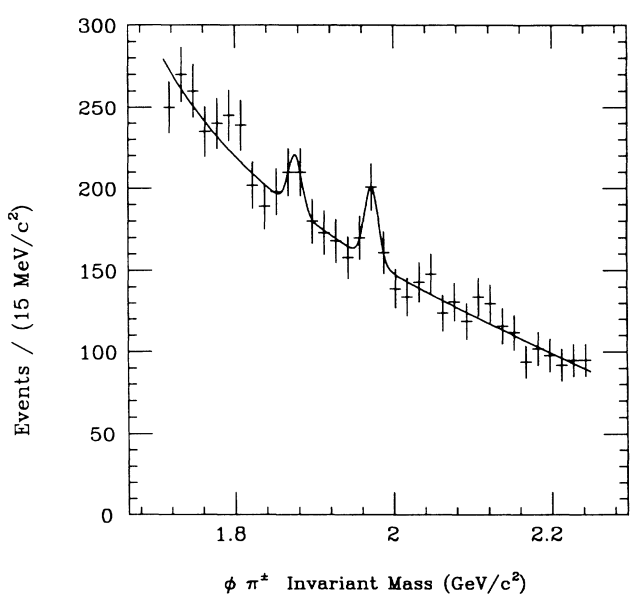

FIG. 3. $\phi\pi^{\pm}$ mass spectrum with ϕ decay-angle cut.

Although the significance of the $D^{\pm} \rightarrow \phi\pi^{\pm}$ signal present in Fig. 3 is only ≈ 2 standard deviations, it may be of interest to compare the yield of $D_s^{\pm}$ and $D^{\pm}$ events. Correcting the raw number of signal events obtained from the fit of Fig. 3 for possible differences in $D_s^{\pm}$ and $D^{\pm}$ acceptance and triggering efficiencies using the weighting method described later in this paper, we obtain an acceptance-corrected event fraction of $N_{D^{\pm}}/(N_{D^{\pm}}+N_{D_s^{\pm}})=0.38\pm0.17$, where both $N_{D^{\pm}}$ and $N_{D_s^{\pm}}$ refer to the number of decays observed in the $\phi\pi^{\pm}$ decay mode over the x_F range from 0.05 to 0.30 ($x_F=2p_{\parallel,\mathrm{c.m.}}/\sqrt{s}$).

We have obtained an estimate for $B\sigma$ for the $D_s^{\pm} \rightarrow \phi\pi^{\pm}$ process in the region $0.05<x_F<0.30$ by dividing the acceptance-corrected event yield by the luminosity determined by counting relatively unbiased inelastic neutron interactions originating in our target. The x_F for a given combination was computed from the measured energy of a $D_s^{\pm}$ candidate, and the incident neutron energy as reconstructed through calorimetry. Here $B\equiv\Gamma(D_s^{\pm}\rightarrow\phi\pi^{\pm})/\Gamma(D_s^{\pm}\rightarrow \text{all})$, and our cross sections are presented with the value 0.495 for the branching fraction $\Gamma(\phi\rightarrow K^+K^-)/\Gamma(\phi\rightarrow\text{all})$ incorporated. A relatively model-independent measurement of the corrected event yield was made by our fitting a weighted $\phi\pi^{\pm}$ invariant-mass distribution for all combinations which satisfy the particle identification, angular distribution, and multiplicity cuts. The combinations entering this histogram were individually weighted by the reciprocal of the $D_s^{\pm}$ acceptance, which was parametrized as a function of $x_F(D_s^{\pm})$ alone, and in this way averaged over all other relevant production and decay variables. As a check, we obtained an alternative acceptance-corrected event yield by fitting a weighted $\phi\pi^{\pm}$ mass distribution for $D_s^{\pm}$ candidates with weights parametrized in terms of the measured $D_s^{\pm}$ energy rather than x_F. We required events to have a $D_s^{\pm}$ energy between 45 and 145 GeV—an energy range chosen to correspond to the previous x_F range at our average neutron energy. This alternative yield estimate was found to be completely consistent but 15% lower than the yield estimate from the x_F parametrized acceptance-correction technique.

The sample luminosity was measured by our counting the number of unbiased neutron interactions as recorded by the coincidence between the target region scintillation counter and downstream scintillation hodoscope and dividing by the previously measured[9] topological cross sections averaged over our target materials after correction for triggering losses (0.15) and live time (0.40). We obtain a partial cross section of $B[\sigma(D_s^+)+\sigma(D_s^-)]=1.51\pm0.43$ μb/nucleon in the range $0.05<x_F<0.30$, where we have assumed a linear A dependence for the hadronic charm cross section. Within the kinematic region covered by our data we find the ratio of charges to be $D_s^+/D_s^-=1.9\pm1.5$, which is consistent with symmetric particle and antiparticle production. Under this symmetric production assumption, the D_s^+ inclusive production cross section would be $B\frac{1}{2}[\sigma(D_s^+)+\sigma(D_s^-)]=0.76\pm0.21$ μb/nucleon. Correcting for the x_F range, we obtain the differential cross section

$$B\tfrac{1}{2}\left[\frac{d\sigma(D_s^+)}{dx_F}+\frac{d\sigma(D_s^-)}{dx_F}\right]$$

$$=2.85\pm0.80\pm0.86\ \mu\text{b/nucleon at } x_F=0.175.$$

In addition to the statistical error (±0.80) we have included a systematic uncertainty in the cross section of $\approx 30\%$ due to errors in the luminosity ($\pm20\%$), model dependence ($\pm20\%$), and differences due to the parametrization of the acceptance ($\pm10\%$). This value assumes a nuclear dependence of the form $A^{1.0}$. The cross section is sensitive to the value of α assumed for the nuclear A^{α} dependence. A $\pm10\%$ change of α about 1.0 will result in a $\pm30\%$ change in σ.

It is interesting to compare this value for the hadronic D_s^+ production cross section to the hadronic cross section for other charmed species. We have previously measured[10] the average of the D^{*+} and D^{*-} inclusive cross sections to be $B\,d\sigma/dx_F=2.11\pm0.43\pm0.63$ μb/nucleon at $x_F=0.07$ in the decay sequence $D^{*+}\rightarrow D^0\pi^+$, $D^0\rightarrow K^+K^-$. Extrapolating both the $D_s^{\pm}$ and $D^{*\pm}$ differential cross sections to $x_F=0$ by assuming a common x_F dependence of the form $d\sigma/dx_F\propto(1-|x_F|)^N$ with N in the range from 3 to 5, we obtain the ratio

$$\frac{B(D_s)\,d\sigma(D_s)/dx_F}{B(D^*)\,d\sigma(D^*)/dx_F}=2.18\pm1.08 \text{ at } x_F=0.$$

After correcting by the measured D^* branching ratio,[8] $B(D^*)=0.314\%$, and a composite of estimates[11] for the D_s, $B(D_s)=3.6\%$, we obtain the ratio

$$\frac{d\sigma(D_s)/dx_F}{d\sigma(D^*)/dx_F}=0.19\pm0.09 \text{ at } x_F=0.$$

We have not included errors on the relevant charm branching ratios, since we know of no way of estimating these errors for the decay mode $D_s\rightarrow\phi\pi$.

It may be of interest to compare our cross sections with those from another experiment with a comparable beam. Ammar *et al.*[12] report on hadronic total cross sections for neutral and for charged charm species which are on the order of tens of microbarns. Under our assumptions about branching ratios, A dependence, and x_F dependence,[13] the cross sections we report imply lower limits which are on the order of 50 microbarns per nucleon for charged species (based on the D_s^+) and a few hundred microbarns per nucleon for neutral species (based on the D^{*+}). If the assumptions are correct, a considerable discrepancy appears to exist.

In conclusion, we have measured the average of the D_s^+ and D_s^- hadroproduced inclusive cross sections into the mode $D_s^{\pm} \rightarrow \phi\pi^{\pm}$ to be

$$B\frac{d\sigma}{dx_F} = 2.85 \pm 0.80 \pm 0.86 \frac{\mu b}{\text{nucleon}} \quad \text{at } x_F = 0.175$$

for high-energy neutrons incident on a fixed target assuming a linear A dependence.

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[13]We assume $d\sigma/dx \propto (1-|x|)^5$.