Charm Hadronic Decays

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In this paper, we report recent results on charm hadronic decays using data taken at E831/FOCUS experiment which is a photo-production experiment at Fermilab. During its 1996-1997 run, we obtained more than 1 million high quality charm particles. Using this sample we study Dalitz plot analysis of D^+ and $D_S^+ \to \pi^+\pi^-\pi^+$ using K-matrix formalism, high multiplicity charm mesons decays of many bodies and the measurements of excited charm resonant states.

1. Introduction

Investigation of charm-quark sector are fundamental to understand flavor physics. Since charm is the only up-type quark for which the decay modes can be studied, it has a unique role to investigate flavor physics and probe Standard Model. This paper summarizes the recent result on FOCUS/E831 collaboration on topics of charm hadronic decays. We describe the results on charm hadronic decays which includes Dalitz plot analysis of D^+ and $D_S^+ \to \pi^+\pi^-\pi^+$ using K-matrix formalism, D decays to K_SK_SX, four-body, five-body and six-body D meson decays and the measurements of $L=1$ excited charmed meson states.

The FOCUS/E831 spectrometer is an upgraded version of the E687 fixed target spectrometer located in the Fermilab proton beam area. It is designed to study charm particles produced by a 180 GeV photon beam on a BeO target. The spectrometer consists of a precise silicon micro vertex system, proportional wire chambers with two dipole magnets, threshold Čerenkov systems, electromagnetic and hadronic calorimeters and muon identification systems. At the FOCUS experiment, vertexing is the key. We can separate the primary vertex and secondary vertex using silicon detector [1]. Particle identification is performed by three Čerenkov counters, two electromagnetic calorimeters, a hadronic calorimeter, and by a system of muon detectors.

During the 1996-1997 fixed target run, more than 1 million charm particles has been fully reconstructed. Using this sample, we study charm hadronic decays.

2. Dalitz plot analysis of D^+ and $D_S^+ \to \pi^+\pi^-\pi^+$ using K-matrix formalism

Charm Dalitz plot provides a probe of charm decay mechanism and charm CP violation. However, the isobar model has problems when adding broad Breit-Wigner signals due to violation of unitarity. Therefore, unitarity can be achieved from K-matrix formalism [2]. FOCUS analysis fits with K-matrix rather than isobar model. We can deal with overlapping scalar states with large widths. Anisovich and Sarantsev parameterize S-wave isoscalar scattering up to 1.9 GeV/c^2 [3]. When we consider 5 virtual states: $\pi\pi$, $K\bar{K}$, 4π, $\eta\bar{\eta}$ and $\eta\eta'$, we find 5 $IJ^{PC} = 00^{++}$ resonance states of $f_0(980), f_0(1300), f_0(1500), f_0(1750), f_0(1200-1600)$. Using this parameterization and adding in vector and tensor particles, we can fit the $D^+, D_S^+ \to \pi^+\pi^-\pi^+$ Dalitz plot. We can see several broad and overlapping resonance states [2]. We can fit it using K-matrix known from scattering data [3], which has been applied to charm decays for the first time. Table 1 shows the result of K-Matrix analysis for D_S^+ and D^+ decays to $\pi^+\pi^-\pi^+$.

For conclusion, the K-matrix formalism has

Table 1
Final results on D_S^+ and $D^+ \to \pi^+\pi^-\pi^+$ fit fraction and phase. The first error is statistical and two systematic errors are quoted. The first systematic error is from the measurement systematics and the second one is due to the particular solution chosen for the K-matrix poles and backgrounds.

Meson	Decay channel	Fit fraction (%)	Phase (deg)
D_S^+	(S-wave) π^+	87.04±5.60±4.17±1.34	0 (fixed)
	$f_2(1270)\pi^+$	9.74±4.49±2.63±1.32	168.0±18.7±2.5±21.7
	$\rho^0(1450)\pi^+$	6.56±3.43±3.31±2.90	234.9±19.5±13.3±24.9
D^+	(S-wave) π^+	56.00±3.24±2.08±0.50	0 (fixed)
	$f_2(1270)\pi^+$	11.74±1.90±0.23±0.18	−47.5±18.7±11.7±5.3
	$\rho^0(770)\pi^+$	30.82±3.14±2.29±0.17	−139.4±16.5±9.9±5.0

The experimental values are given in ref. [2].

been applied for the first time to the charm sector in our Dalitz plot analyses of the D_S^+ and $D^+ \to \pi^+\pi^-\pi^+$ final states. The results are extremely encouraging since the same K-matrix description gives a coherent picture of both two-body scattering measurement in light-quark experiment as well as charm meson decay. For D_S^+ and D^+, the S-wave decay amplitude is production of $KK, \eta\eta, \eta\eta'$. Dipion production is always much smaller. For the D^+, the $s\bar{s}$ contribution competes with a $d\bar{d}$ contribution. This interpretation also bears on the role of the annihilation diagram in the $D_S^+ \to \pi^+\pi^-\pi^+$.

3. Observation of $D^0 \to K_S K_S X$

Detailed measurements of rare and unusual exclusive decay modes of charm mesons provide a powerful way to probe the details of charm decay such as the contributions of W-exchange diagrams and final state interactions. We report on D^0 decay to multi K_S decay mode which includes $K_S K_S$ and $K_S K_S K^\pm \pi^\mp$ and $K_S K_S \pi^\pm \pi^\mp$.

3.1. Observation of $D^0 \to K^0 \bar{K}^0$

The $D^0 \to K^0 \bar{K}^0$ decay is expected to occur primarily via two W-exchange diagrams, which are expected to cancel out in a four-quark model. In the standard six-quark model, due to Cabibbo-Kobashashi-Maskawa matrix elements, the difference between the two amplitudes are tiny of order of 10^{-4}. However, due to final state interactions effects, the branching ratio may be very large as $Br(D^0 \to K^0\bar{K}^0) = \frac{1}{2}Br(D^0 \to K^+K^-) = 0.3\%$ [4]. Therefore, theses measurements help to understand the interplay between the weak and strong interactions. The branching ratio of the $D^0 \to K^0\bar{K}^0$ is measured by $D^0 \to K_S K_S$ mode. As shown in Fig. 1 we get 101 ± 19 events of reconstructed number of $K_S K_S$. The invariant mass is 1.868 ± 0.002 GeV$/c^2$. Using D^0 decays $K_S\pi^+\pi^-$ as a normalization mode, we can get the preliminary relative branching ratio of $Br(D^0 \to K^0\bar{K}^0)/Br(D^0 \to \bar{K}^0\pi^+\pi^-)$ $=(1.62 \pm 0.30)\%$.

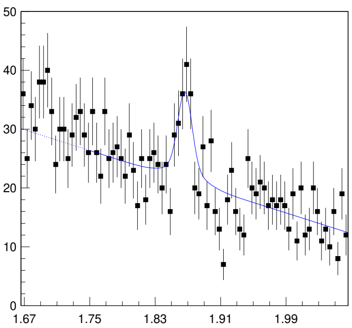

Figure 1. The invariant mass plot of $D^0 \to K_S K_S$.

3.2. Observation of $D^0 \to K_S K_S K^\pm \pi^\mp$

The decays of $D^0 \to \bar{K}^0 \bar{K}^0 K^+ \pi^-$ and $D^0 \to \bar{K}^0 K^0 K^- \pi^+$ can only be separated via $D^{*+} \to D^0 \pi^+$. We will demonstrate a signal for the two channels combined. Then we make invariant mass plot for $D^0 \to K_S K_S K^\pm \pi^\mp$ mode. We get 57 ± 10 events of the reconstructed $K_S K_S K^\pm \pi^\mp$, this is a first observation. We can get the preliminary branching ratio using D^0 decays $K_S \pi^+ \pi^-$ as a normalization mode. The branching ratio of $D^0 \to K^0 \bar{K}^0 K^\pm \pi^\mp$ is around 2.5 $\times 10^{-3}$. This is larger, more like the branching ratio of $D^0 \to K^+ K^- \bar{K}^0 \pi^0$.

3.3. Observation of $D^0 \to K_S K_S \pi^\pm \pi^\mp$

This channel is Cabibbo suppressed and was first observed by the ARGUS Collaboration [5]. This channel has a larger background than the $D^0 \to K_S K_S K^\pm \pi^\mp$ channel due to more phase space and two pions. We get 113 ± 20 events of the reconstructed $K_S K_S \pi^\pm \pi^\mp$. Since the resonant structure for this channel is not known, we use a non-resonant Monte Carlo simulation to compute the branching fraction. We use the simulation of $D^0 \to K^{*-} K^{*+}$ for the systematic errors. We get the preliminary relative branching ratio of $Br(D^0 \to K_S K_S \pi^+ \pi^-)/Br(D^0 \to \bar{K}^0 \pi^+ \pi^-) = 0.0208 \pm 0.0035$.

4. D decays to four-body, five-body and six-body modes

More information on multibody final states in the charm sector provides an essential ability to describe model decays rates and to further our understanding of the decay process in heavy quark systems. This is particularly important for the D_S^+ decays where a substantial part of its hadronic decay rate is still not identified. In this paper, we extended our work on four-body, five-body and six-body involving charged kaon or neutral kaon. Table 2 shows the summary of relative branching ratios.

4.1. Four-body decays with charged kaon (D^0)

The first mode is D^0 decays to $K^- K^+ K^- \pi^+$. The relative branching ratio of $Br(D^0 \to K^- K^+ K^- \pi^+)/Br(D^0 \to K^- \pi^+ \pi^- \pi^+) = (0.257 \pm 0.034 \pm 0.024)\%$ [6].

Compared to the PDG2003 result which is $Br(D^0 \to K^- K^+ K^- \pi^+)/Br(D^0 \to K^- \pi^+ \pi^- \pi^+) = (0.32 \pm 0.09)\%$ [7], we can reduce this error significantly. This mode has several sub resonant states of ϕ and $\bar{K}^{*0}$. Therefore $D^0 \to \phi \bar{K}^{*0}$ is a dominant sub-resonant state.

4.2. Four-body decays with neutral kaon (D^+, D_S^+)

We have also measured hadronic four-body decays of D^+ and D_S^+ mesons with a K_S in the final state [8]. By adding these measurements, we can make the compliment set for the for the four-body decays.

4.3. Five-body decays with charged kaons (D^+, D_S^+)

First we report five-body decays with charged kaons. Then, we report with neural kaons. The first mode is $D^+ \to K^- \pi^+ \pi^+ \pi^+ \pi^-$. The second is $D^+ \to \pi^+ \pi^+ \pi^+ \pi^- \pi^-$. The third is $D^+ \to K^+ K^- \pi^+ \pi^+ \pi^-$ which is the first measurement [9]. We have also measured the branching ratio of $D_S^+ \to \pi^+ \pi^+ \pi^+ \pi^- \pi^-$ and $D_S^+ \to K^+ K^- \pi^+ \pi^+ \pi^-$ [9]. We get relative branching ratios with a significantly reduced error compared to PDG2003 result [7].

4.4. Five-body decays with neutral kaon (D^0, D_S^+)

The next topic, five-body decay modes, are those including K_S. The decay mode is D^0 decays to $K_S^0 \pi^+ \pi^- \pi^+ \pi^-$. Using D^0 decays $K_S^0 \pi^+ \pi^-$ as a normalization mode, we can get the relative branching ratio [10]. We reduce the errors significantly compared to PDG2003 result [7]. We also present the first evidence of the decay mode of $D_S^+ \to K_S^0 K_S^0 \pi^+ \pi^- \pi^+$.

4.5. Resonant analyses of five-body decays

We summarize resonant analyses of five-body decays. We perform incoherent fits using projections. All five-body decay modes show strong vector $\rho - \pi$ contributions. D^+ is consistent with around 60% of $D^+ \to \bar{K}^{*0} a_1(1260)$ [9]. D_S^+ is consistent with almost 100% of $D_S^+ \to \phi a_1(1260)$ [9]. D^0 is also consistent dominated by $D^0 \to K^{*-} a_1(1260)$. All are consistent

Table 2
The relative branching ratios for four-body, five-body and six-body modes. The first error is statistical and the second is systematic. All branching ratios are inclusive of subresonant modes.

Decay mode	FOCUS	Previous Measurement
$\Gamma(D^0 \to K^-K^+K^-\pi^+)/\Gamma(D^+ \to K^-\pi^+\pi^-\pi^+)$	$(0.257 \pm 0.034 \pm 0.024)\%$ [6]	$(0.32 \pm 0.09)\%$ [7]
$\Gamma(D^+ \to K_S K^-\pi^+\pi^+)/\Gamma(D^+ \to K_S\pi^-\pi^+\pi^+)$	$0.0768 \pm 0.0041 \pm 0.0032$ [8]	
$\Gamma(D^+ \to K_S K^+\pi^+\pi^-)/\Gamma(D^+ \to K_S\pi^-\pi^+\pi^+)$	$0.0562 \pm 0.0039 \pm 0.0040$ [8]	
$\Gamma(D^+ \to K_S K^+K^-\pi^+)/\Gamma(D^+ \to K_S\pi^-\pi^+\pi^+)$	$0.0077 \pm 0.0015 \pm 0.0009$ [8]	
$\Gamma(D_S^+ \to K_S K^+\pi^+\pi^-)/\Gamma(D_S^+ \to K_S K^-\pi^+\pi^+)$	$0.586 \pm 0.052 \pm 0.043$ [8]	
$\Gamma(D^+ \to K^-\pi^+\pi^+\pi^+\pi^-)/\Gamma(D^+ \to K^-\pi^+\pi^-)$	$0.058 \pm 0.002 \pm 0.006$ [9]	$0.077 \pm 0.008 \pm 0.010$ [11]
$\Gamma(D^+ \to \pi^+\pi^+\pi^+\pi^-\pi^-)/\Gamma(D^+ \to K^-\pi^+\pi^-\pi^+\pi^-)$	$0.290 \pm 0.017 \pm 0.011$ [9]	$0.299 \pm 0.061 \pm 0.026$ [11]
$\Gamma(D_S^+ \to \pi^+\pi^+\pi^+\pi^-\pi^-)/\Gamma(D_S^+ \to K^-K^+\pi^+)$	$0.145 \pm 0.011 \pm 0.010$ [9]	$0.158 \pm 0.042 \pm 0.031$ [11]
$\Gamma(D_S^+ \to K^+K^-\pi^+\pi^+\pi^-)/\Gamma(D_S^+ \to K^-K^+\pi^+)$	$0.150 \pm 0.019 \pm 0.025$ [9]	$0.188 \pm 0.036 \pm 0.040$ [11]
$\Gamma(D^+ \to K^+K^-\pi^+\pi^+\pi^-)/\Gamma(D^+ \to K^-\pi^+\pi^+\pi^+\pi^-)$	$0.040 \pm 0.009 \pm 0.019$ [9]	
$\Gamma(D^0 \to K_S^0\pi^+\pi^+\pi^+\pi^-)/\Gamma(D^0 \to K_S^0\pi^+\pi^-)$	$0.095 \pm 0.005 \pm 0.007$ [10]	0.107 ± 0.029 [12]
$\Gamma(D_S^+ \to K_S^0 K_S^0\pi^+\pi^+\pi^-)/\Gamma(D_S^+ \to K_S^0 K^-\pi^+\pi^-)$	$0.102 \pm 0.029 \pm 0.029$ [10]	
$\Gamma(D^0 \to K_S^0 K^-\pi^+\pi^+\pi^-)/\Gamma(D^0 \to K_S^0\pi^+\pi^+\pi^-\pi^-)$	< 0.054 (90% CL) [10]	
$\Gamma(D^0 \to K^-\pi^+\pi^+\pi^+\pi^-\pi^-)/\Gamma(D^0 \to K^-\pi^+\pi^+\pi^-)$	$(0.270 \pm 0.058 \pm 0.038)\%$ [13]	
$\Gamma(D^0 \to \pi^+\pi^+\pi^+\pi^-\pi^-\pi^-)/\Gamma(D^0 \to K^-\pi^+\pi^+\pi^-)$	$(0.523 \pm 0.059 \pm 0.135)\%$ [13]	
$\Gamma(D^0 \to \pi^+\pi^+\pi^+\pi^-\pi^-\pi^-)/\Gamma(D^0 \to K^-\pi^+\pi^+\pi^+\pi^-\pi^-)$	$1.93 \pm 0.47 \pm 0.48$ [13]	

dominated by vector $a_1(1260)$ with $a_1(1260) \to \rho^0\pi^+$ [10].

Lipkin proposed that heavy flavor decays in which a radiated W hadronizes to one particle and the remaining quarks hadronize into another particle might exhibit some universality [14]. We can look at decays of the form

$$R(ifX) \equiv \frac{Br(i \to fX)}{Br(i \to f\rho)} \sim |\frac{W \to X}{W \to \rho}|^2$$

where i stands for initial state and f stands for final state. Studies of five-body charm decays by FOCUS have provided evidence for this model with five-body decays of D^0, D^+, and D_S^+ being dominated by quasi-two-body decays involving the $a_1(1260)^\pm$.

4.6. Six-body decays with charged kaons (D^+, D_S^+)

Even if hadronic decays of charmed mesons have been extensively studied in recent years, six-body hadronic decays of the D^0 decays has not been previously observed. The FOCUS experiment presents the first branching ratio measurement of the $D^0 \to K^-\pi^+\pi^+\pi^+\pi^-\pi^-$ and $D^0 \to \pi^+\pi^+\pi^+\pi^-\pi^-\pi^-$. The relative branching ratio of $Br(D^0 \to K^-\pi^+\pi^+\pi^+\pi^-\pi^-)/Br(D^0 \to K^-\pi^+\pi^+\pi^-) = (2.70 \pm 0.58 \pm 0.38) \times 10^{-3}$ [13]. This shows that six-body branching fraction is small compared to four-body decays.

The relative branching ratio of $Br(D^0 \to \pi^+\pi^+\pi^+\pi^-\pi^-\pi^-)/Br(D0 \to K^-\pi^+\pi^+\pi^+\pi^-\pi^-) = 1.93 \pm 0.47 \pm 0.48$ [13], which shows the relative branching ratio between Cabibbo suppressed mode and Cabibbo favored mode is 1.93. Strangely, Cabibbo suppressed branching ratio is larger than Cabibbo favored mode. Theoretical discussions of many-body charm decays has suggested a "vector dominant model" in which a charmed meson emits a $W^\pm$ which hadronizes into a charged vector, axial vector, or pseudoscalar meson [14].

5. Excited Charm Resonant States

This paper also reports new FOCUS results on $L = 1$ $c\bar{u}$, $c\bar{d}$, $c\bar{s}$ states. In the limit of infinitely heavy quark mass, the heavy-light meson behaves analogously to the hydrogen atom. The heavier quark does not contribute to the orbital degree of freedom which are completely defined by light quark. According to Heavy Quark Symmetry(HQS), there are the spectrum of excited charmed states [15–19].

The angular momentum of the heavy quark is described by its spin S_Q and that of the light degrees of freedom are described by $j_q = s_q + L$, where s_q is the light quark spin and L is the orbital angular momentum of light quark. The quantum numbers of S_Q and j_q are individually conserved. The quantum numbers of the excited $L = 1$ states are formed by combining S_Q and j_q. For $L = 1$ we have $j_q = 1/2$ and $j_q = 3/2$. When combined with S_Q they provide two $j_q = 1/2$ ($J = 0, 1$ where J is the total angular momentum of the excited charm meson) states, there four states will be denoted by $D_0^*, D_1(j_q = 1/2), D_1(j_q = 3/2)$ and D_2^* [20].

$L = 1$ charm meson were reconstructed via $D^+\pi$ and $D^0\pi^+$ where D^0 decays were reconstructed in the channels $D^0 \to K^-\pi^+$ and $D^0 \to K^-\pi^+\pi^-\pi^+$. D^+ decays were reconstructed in the channels $D^+ \to K^+\pi^-\pi^+$. In this paper, we will describe D_2^{*+} and D_2^{*0} measurement which decays to $D\pi^\pm$ and an evidence for D_0^* contributions.

Photoproduction experiments give significant yields with low multiplicity. Process at the FOCUS experiments of the type are $\gamma N \to D^0\pi^+X$ where D^0 decays to $K^-\pi^+$ and $K^+\pi^-\pi^+\pi^-$. The other process is $\gamma N \to D^+\pi^-X$ where $D^+ \to K^+\pi^-\pi^+$.

Fig. 2 shows the distributions of the invariant mass differences of $\Delta M_0 \equiv M((D^+)\pi^-) - M(D^+) + M_{D^+}$ and $\Delta M_+ \equiv M((D^0)\pi^+) - M(D^0) + M_{D^0}$, where $M(D^+)$ and $M(D^0)$ are the invariant masses of $D^+ \to K^-\pi^+\pi^+$ and $D^0 \to K^-\pi^+, K^-\pi^+\pi^-\pi^+$ respectively [20]. M_{D^+} and M_{D^0} are the world average of D^+ and D^0 masses. We consider feed down from D_2^* and D_1 partially reconstructed. Fit improves dramatically with inclusion of a broad S-wave state. This might be D_0^* decay to $D\pi$ or D_1' decay $(D^*\pi)\gamma$ with missing gamma.

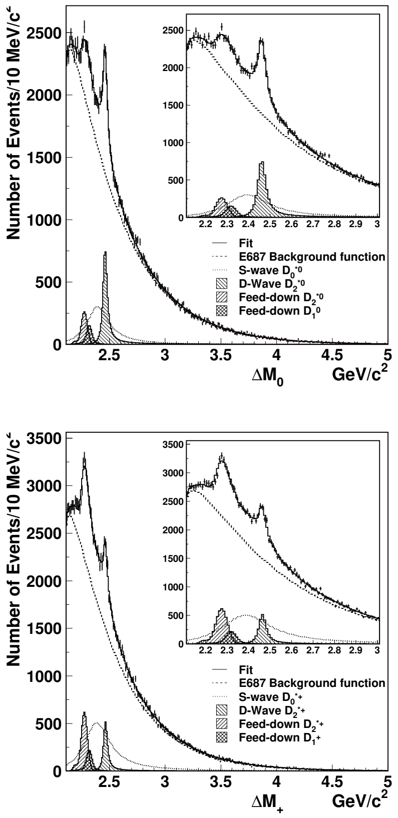

Figure 2. The fit to the ΔM_0 and ΔM_+ mass spectra including a term for an S-wave resonance.

The results show precise measurements of the D_2^* parameters with comparable statistical errors to the previous world averages and the first evidence for the expected broad D_0^* states.

6. Conclusions

Charm physics gives a rich source of new results. With the large statistics in charm, FOCUS experiment is playing a major role in understanding the charm hadronic decays. For the first time the K-matrix approach has been applied to charm decays. The FOCUS experiment also shows the discovery of new multibody final states, new precise measurement of D_2^{*+} and D_2^{*0}, and evidence for broad D_0^{*0} and D_0^{*+}.

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