Study of the Doubly Cabibbo-Suppressed Decay $D^+ \to \phi K^+$ and the Singly Cabibbo-Suppressed Decay $D_s^+ \to \phi K^+$

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We have searched for the doubly Cabibbo-suppressed decay $D^\pm \to \phi K^\pm$ and the singly Cabibbo-suppressed decay $D_s^\pm \to \phi K^\pm$ in data from the Fermilab photoproduction experiment E691. The $D^\pm$ decay mode is of particular interest because it cannot result from simple spectator decay. We observe a $D^\pm$ signal corresponding to a branching ratio of $B(D^\pm \to \phi K^\pm) = (3.3^{+1.8}_{-1.5} \pm 0.8) \times 10^{-4}$. In the $D_s^\pm$ mode we measure an upper limit $B(D_s^\pm \to \phi K^\pm) < 0.2\%$.

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Most of the Cabibbo-allowed decays of D mesons are now accounted for, as are many of the Cabibbo-suppressed decays [1]. These measurements allow a fairly systematic study of the mechanism of nonleptonic charm decay. But there are also the so-called doubly Cabibbo-suppressed decays (DCSD), which are characterized by a $\Delta C = -\Delta S$ rule, such as in the decay $D^+ \to \rho K^+$ (throughout this paper the charge conjugate states are implicitly included), in contrast to Cabibbo-allowed decays which follow the $\Delta C = \Delta S$ rule. It is interesting to pursue the study of DCSD modes, not only to test our understanding of the decay mechanism [2], but also because it will aid in the interpretation of searches for D^0-$\bar{D}^0$ mixing [3,4].

No observations of doubly Cabibbo-suppressed decays have been published. This is not surprising, given that the typical branching ratio for the dominant spectator DCSD modes can be roughly estimated to be about 0.03%. This comes from a branching ratio of about 10% for a typical Cabibbo-allowed spectator mode, times the factor $\tan^4\theta_c$ which stands for a double Cabibbo suppression.

In Cabibbo-allowed decays, nonspectator contributions are generally smaller than the spectator contributions, most notably in the case of $D_s^+ \to \rho\pi^+$ [5]. The one clear exception to this rule is in $D^0 \to \phi\bar{K}^0$, which does have a relatively large branching ratio [1]. Thus we can say that the decay mode $D^+ \to \phi K^+$ is a special DCSD case because it cannot result from the simple spectator decay amplitude, shown in Fig. 1(a), which is naively expected to dominate the total decay rate. To get rid of the $\bar{d}$ quark from the D^+ we need some nonspectator process such as W annihilation, as in Fig. 1(b), or final-state rescattering via some intermediate state, as pointed out by Donoghue [6] whose approach is depicted in Fig. 1(c). Thus the $D^+ \to \phi K^+$ branching ratio should be even smaller than the typical DCSD, which we roughly estimated in the previous paragraph, unless it is enhanced in the same manner as that for $D^0 \to \phi\bar{K}^0$.

No singly Cabibbo-suppressed (SCSD) decays of the D_s^+ have been observed. The decay $D_s^+ \to \phi K^+$ can proceed by the same nonspectator diagrams as discussed for the D^+, but with only one Cabibbo suppression. In addition, the two spectator diagrams can contribute to this decay. They may destructively interfere in the same way as the corresponding two spectator amplitudes for allowed D^+ decays (e.g., $D^+ \to \bar{K}^{*0}\pi^+$). If only those spectator diagrams contribute, the branching ratio should

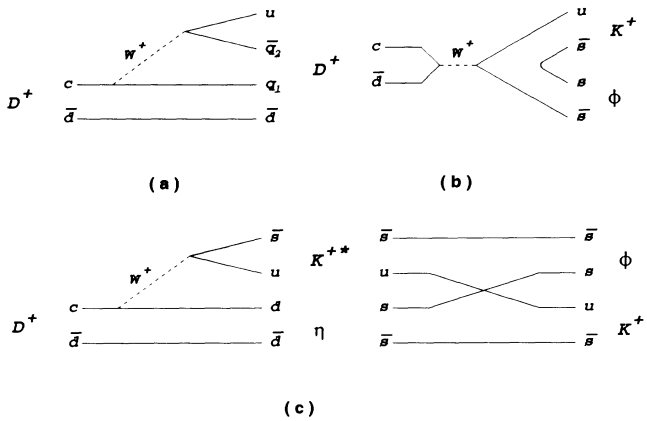

FIG. 1. Some quark diagrams for D^+ meson decays: (a) spectator diagram; (b) contribution from annihilation diagram for $D^+ \to \phi K^+$ channel; and (c) contribution of final-state rescattering effect in $D^+ \to \phi K^+$ channel.

be roughly 0.02%. A penguin diagram can also contribute to $D_s^+ \to \phi K^+$, with a strength which is hard to estimate.

In this paper we report the results of sensitive searches for the DCSD mode $D^+ \to \phi K^+$ and also the SCSD mode $D_s^+ \to \phi K^+$. The results presented here are from E691, a high-energy photoproduction experiment at the Fermilab Tagged Photon Spectrometer. The two-magnet spectrometer had a large acceptance, with drift chambers to measure momentum, Čerenkov counters to identify charged hadrons, and calorimetry used for lepton identification and for the trigger. In addition, a series of silicon microstrip detectors were used to find separate production and decay vertices, making it possible to reduce the noncharm background. Photons of average energy 145 GeV/c^2 struck a 5-cm beryllium target. More details on the detector can be found elsewhere [7].

We looked for the decay chain $D^+ \to \phi K^+$, where $\phi \to K^+K^-$. We selected events containing three kaons with high joint Čerenkov probability [7], reducing the background by a factor of 1000. We required also one K^+K^- pair with an invariant mass lying in a 15-MeV/c^2-wide mass window centered at the nominal ϕ mass, as shown in the typical K^+K^- mass spectrum of Fig. 2. The above requirements combined were strong enough to reduce the contamination from pions and protons in the K^+K^- pair to a very low level. Then we demanded a tighter identification requirement for the non-ϕ kaon, to reduce further the nonkaon contamination.

We also applied most of the common E691 vertex requirements [7], namely, we required these tracks to form a well-constrained vertex, the line of flight of the reconstructed charm candidate to pass within 60 μm of a reconstructed primary vertex candidate. To reduce the noncharm background, only charm candidates were chosen which decayed at least a distance $L = 13\sigma$ downstream of the primary vertex, where σ is the error in the distance between primary and secondary vertices (typically 300 μm for a 60-GeV/c charmed particle, and linearly dependent on momentum). In addition, if any other track in the event passed within 80 μm of the secondary vertex, this event was discarded.

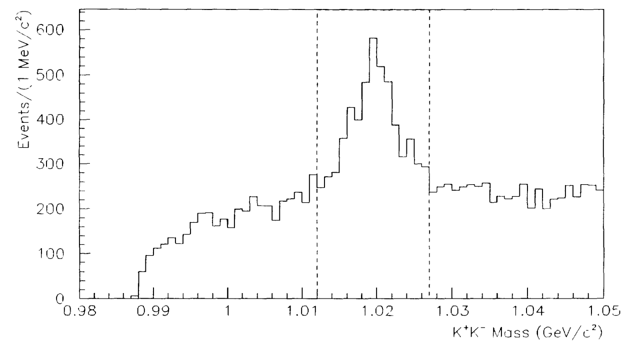

FIG. 2. Typical K^+K^- mass spectrum in E691 data, after loose kaon identification requirements.

The possible feedthroughs from misidentification of the more abundant decays $D^+(D_s^+) \to \phi\pi^+$ were investigated using the $\phi\pi^+$ mass spectrum of the candidates which pass the ϕK^+ selection, which is shown in Fig. 3. The plot shows 2 D^+ and 3 D_s^+ events, with almost no background. Because the background level in this plot is so low, we can remove these events with a cut around the two narrow peaks, without significantly distorting the underlying background. The dips caused in the ϕK^+ mass spectrum are about 50 MeV/c^2 in width, centered at 2.0 and 2.1 GeV/c^2, with an integrated area of 0.2 and 0.05 event. They thus have negligible effect on the number of events observed in the D^+ and D_s^+ peaks when fitting the ϕK^+ mass plot.

The ϕK^+ mass spectrum for all combinations after the feedthroughs are removed is shown in Fig. 4(a). The curve shown is the projection of the results of a two-dimensional maximum likelihood fit to the distribution in mass and cosθ, where θ is the angle between the two positive kaons in the ϕ rest frame. To fit the mass spectrum,

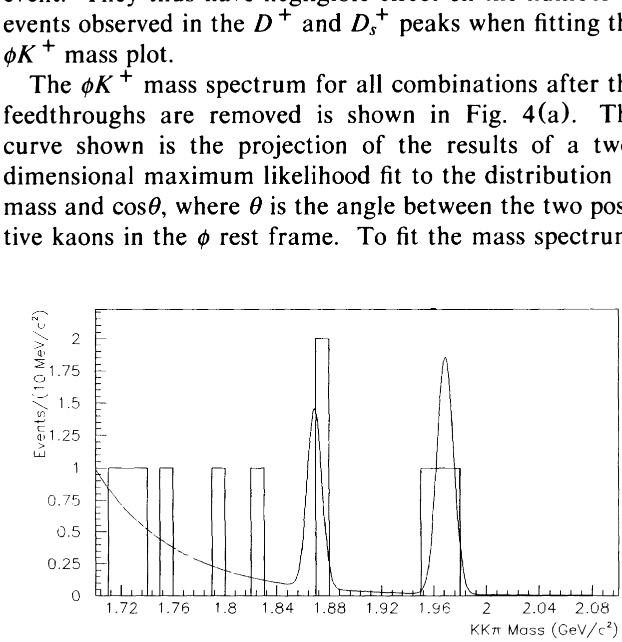

FIG. 3. Invariant $\phi\pi^+$ mass spectrum of selected ϕK^+ events.

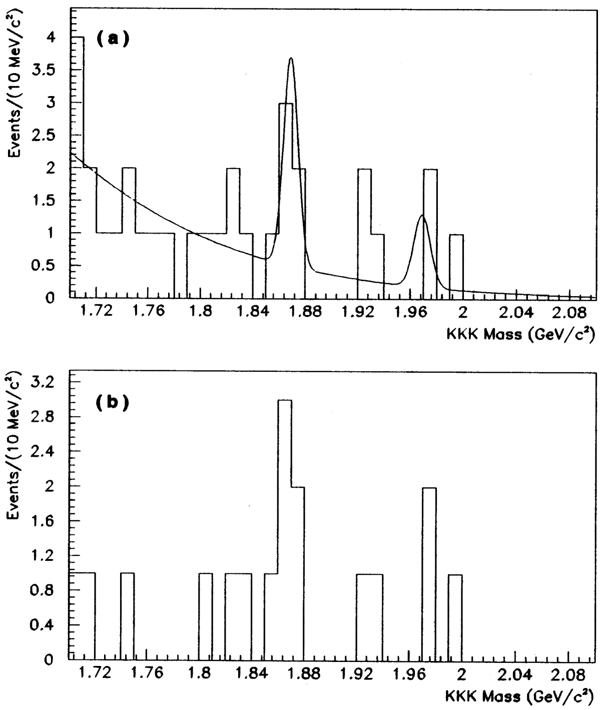

FIG. 4. Invariant ϕK^+ mass spectra of selected events: (a) events used in the maximum likelihood fit described in the text; (b) spectrum with the additional requirement $|\cos\theta| > 0.5$.

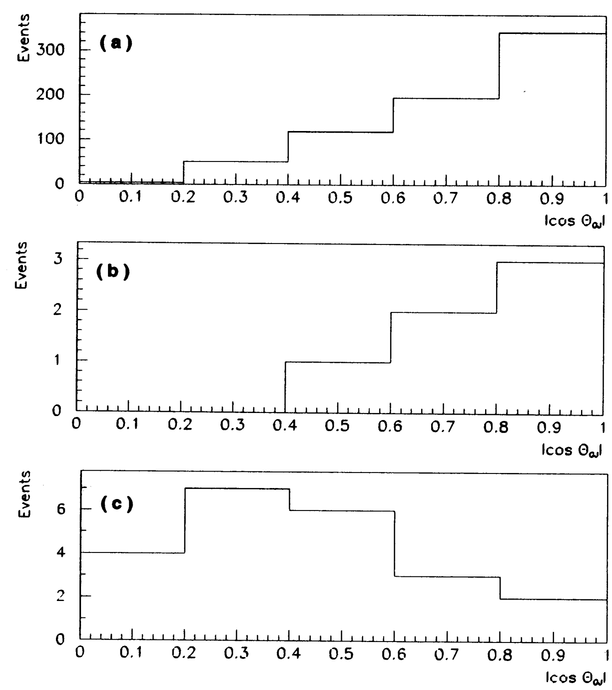

FIG. 5. Comparison of $|\cos\theta|$ distributions: (a) Monte Carlo simulated events; (b) real data, D^+ mass region; and (c) real data, outside D^+ mass region.

we use two Gaussians at the D^+ and the D_s^+ masses, over a background parametrized with a smooth exponential modulated by a linear function. The resulting number of events in the peaks are $4.5^{+2.4}_{-2.0}$ D^+ and $1.8^{+1.7}_{-1.1}$ D_s^+ decays. Setting each of the signals to zero lowers the log of the likelihood function by 5.4 units for D^+ and by 2.1 units for D_s^+. Figure 4(b) shows the ϕK^+ mass spectrum of those events satisfying $|\cos\theta| > 0.5$, which would retain 91% of the signal while rejecting 50% of background. The angular distribution is shown for the signal and background regions in Fig. 5. It shows that the signal region is consistent with the expected $\cos^2\theta$ distribution, while the background is consistent with a flat distribution.

The overall detection efficiency, with statistical errors only, was found to be $(4.80 \pm 0.18)\%$ for $D^+ \to \phi K^+$ and $(1.66 \pm 0.17)\%$ for $D_s^+ \to \phi K^+$. To turn the observed signals into branching ratios we compare them to the correspondent $\phi\pi^+$ signals seen in the E691 data. For D^+ we find

$$\frac{B(D^+ \to \phi K^+)}{B(D^+ \to \phi\pi^+)} = (5.8^{+3.2}_{-2.6} \pm 0.7) \times 10^{-2}. \qquad (1)$$

Using $B(D^+ \to \phi\pi^+) = (5.7 \pm 1.1) \times 10^{-3}$ [1], we find

$$B(D^+ \to \phi K^+) = (3.3^{+1.8}_{-1.5} \pm 0.8) \times 10^{-4}. \qquad (2)$$

For the D_s^+ the result is

$$\frac{B(D_s^+ \to \phi K^+)}{B(D_s^+ \to \phi\pi^+)} = (2.6^{+2.5}_{-1.7} \pm 0.5) \times 10^{-2} < 7.1 \times 10^{-2} \text{ (90\% C.L.)}. \qquad (3)$$

Using the $D_s^+ \to \phi\pi^+$ branching ratio of approximately 3% [1,8], this corresponds to an upper limit $B(D_s^+ \to \phi K^+) < 0.2\%$.

The systematical errors estimated for our measurements, relative to the observed number of $D^+ \to \phi K^+$ ($D_s^+ \to \phi K^+$) events, are 7% (9%) from background parametrization, 7% (8%) from variations in the vertex requirements for event selection, 6% (6%) from kaon reconstruction, 3% (10%) from the $\phi\pi$ feedthrough treatment, and 5% (6%) from other minor sources. Combining in quadrature all those contributions one obtains a total systematic error of 13% (0.6 event) for $D^+ \to \phi K^+$, and 18% (0.3 event) for $D_s^+ \to \phi K^+$.

The $D^+ \to \phi K^+$ branching ratio we have measured is comparable with the expectations for the largest DCSD branching ratios [2]. This is rather surprising, given that this process does not proceed by simple spectator decay.

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