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A study of Cabibbo-suppressed D^0 decays

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Abstract. Using the ARGUS detector at the e^+e^- storage ring DORIS II, we have measured branching ratios for the Cabibbo-suppressed decays $D^0 \to \pi^- \pi^+$, $D^0 \to K^- K^+$, and $D^0 \to K_s^0 K^- \pi^+$, observed the Cabibbo-allowed decay $D^0 \to K_s^0 K_s^0 K_s^0$ and obtained an upper limit on the branching ratio for $D^0 \to K^0 \bar{K}^0$.

1 Introduction

The study of Cabibbo-suppressed D^0-decays is an important means of probing the interplay between the weak and strong interactions. Much theoretical and experimental attention has been given to the understanding of Cabibbo-allowed channels, culminating in a coherent picture of heavy mesons decays [1–7]. Now that experiments are reaching a level of sensitivity which allows the systematic study of the Cabibbo-suppressed channels, these ideas can and should be further tested. One particularly interesting feature of Cabibbo-suppressed D^0 decays is the ratio between the branching ratios for the $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ channels. Assuming SU(3) flavour symmetry, one would expect this ratio to be close to unity. However, the MARK II [8] and MARK III [9] collaborations have reported experimental values of approximately 3.7. There have been theoretical attempts to explain this discrepancy by final state interactions [10, 11] or even by a contribution from penguin diagrams [12]. A more precisely measured value would be of obvious interest.

In this paper we discuss measurements of the Cabibbo-suppressed decays $D^0 \to \pi^- \pi^+$, $D^0 \to K^- K^+$, $D^0 \to K_s^0 K^- \pi^+$, and $D^0 \to K^0 \bar{K}^0$, and also present evidence for the Cabibbo-allowed decay $D^0 \to K_s^0 K_s^0 K_s^0$.

2 Data analysis

The data sample used for these studies corresponds to an integrated luminosity of $340\,pb^{-1}$ obtained with the ARGUS detector at the DORIS II storage ring on the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(4S)$ resonances, and in the nearby continuum. The ARGUS detector is a 4π spectrometer described in detail in [13]. Charged particle identification is made on the basis of specific ionization and time-of-flight measurements, which are combined into a likelihood ratio for each of the allowed hypotheses e, μ, π, K, and p. All particle hypotheses with a likelihood value in excess of 1% were accepted.

In this study, we have reconstructed D^0 mesons originating in the decay $D^{*+} \to D^0 \pi^+$ ⋆. This technique exploits the small Q value of the D^{*+} decay in order to obtain signals with very low backgrounds.

D^0 mesons were reconstructed in a total of 6 decay channels: $D^0 \to K^- \pi^+$, $D^0 \to K^- K^+$, $D^0 \to \pi^- \pi^+$, $D^0 \to K_s^0 K^- \pi^+$, $D^0 \to K_s^0 K_s^0$, and $D^0 \to K_s^0 \pi^- \pi^+$. Combinations with poorly measured tracks and therefore large errors on the determined mass of the D^0 candidate were rejected, by requiring this error to be less than 30 MeV/c^2. D^0 candidates were further required to have a measured mass within two standard deviations of the accepted D^0 mass; mass resolutions for all channels were determined by Monte Carlo and were found to range from 15 MeV/c^2 for $D^0 \to K_s^0 \pi^- \pi^+$ to 22 MeV/c^2 for $D^0 \to \pi^- \pi^+$. For all surviving candidates, a kinematic fit was performed which constrained the mass to the accepted D^0 mass. These candidates were then combined with all appropriately charged pions in the same event in order to look for a D^{*+} signal.

Due to the observation that the fragmentation of primary charmed quarks produces a hard D^{*+} momentum spectrum, all $D^0 \pi^+$ combinations were required to satisfy $x_p(D\pi) > 0.5$, where the scaled momentum of the $D\pi$ combination, $x_p(D\pi)$, is defined by $x_p(D\pi) = p(D\pi)/p_{\max}$. This requirement greatly reduces the combinatorial background, whose momentum spectrum is peaked sharply at low values of x_p.

Specific details of the analysis of the various D^0 decay modes under study will be presented below.

3 $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ decays

The distribution of $\cos\theta_-$, where θ_- is the angle between the negatively charged particle from the D^0 decay and the D^0 boost direction, as measured in the D^0 rest frame, should be isotropic. In contrast, the distribution of random $K^- \pi^+$ and $\pi^- \pi^+$ combinations tends to peak strongly at small forward and backward angles. Therefore, for channels $D^0 \to K^- \pi^+$ and $D^0 \to \pi^- \pi^+$ we required $|\cos\theta_-| < 0.85$ in order to further suppress combinatorial background.

For the $K^- K^+$ channel, the likelihood ratio for kaon identification was required to be larger than 10% in order to reduce the number of background events. The same cut was used in the $D^0 \to K^- \pi^+$ analysis, against which the normalization was performed.

Of particular importance for these analyses is particle misidentification, since misidentification of only one of the particles in the decay $D^0 \to K^- \pi^+$ can feed events into the Cabibbo-suppressed channels.

In order to study this correlated background we reconstructed D^0 mesons in the $D^0 \to K^- \pi^+$ decay channel and applied the mass-constraining kinematic fit to all $K^- \pi^+$ combinations with an invariant mass

⋆ References to a specific particle state should be interpreted as implying the charge-conjugate state also within 80 MeV/c^2 of the D^0 mass (approximately $\pm 4\sigma$). A charged pion was then added in order to look for a D^{*+} signal. For combinations from the D^{*+} peak we then assigned the K^+ hypothesis to the π^+ from the D^0 decay and looked for a D^{*+} signal from the fake K^-"K^+" combinations. The events which passed all selection criteria for the $K^- K^+$ channel were then considered as a misidentification background for $D^0 \to K^- K^+$ decay. In fact, due to the existence of some combinatorial background under the D^{*+} peak, this procedure overestimates the actual background.

Defining ΔM as the mass difference between the nominal D^0 mass and that of the K^-"K^+" combination, we have plotted, in Fig. 1b, the entries in the $\Delta M - \cos\theta_-$ plane for all misidentification background events obtained in this manner. Due to $\pi^+ \to$"K^+" misidentification, the K^-"K^+" combinations populate a region of positive ΔM and negative $\cos\theta_-$. The ΔM behaviour results from the assignment of the kaon mass to a pion. The $\cos\theta_-$ trend can be understood to result from the increase of the pion-kaon misidentification probability with increasing momentum; negative $\cos\theta_-$ entries arise from those events in which the misidentified particle is going forward with respect to the D^0 boost direction and therefore has a large momentum in the lab frame. This source of background is removed completely by requiring that all accepted K^+K^- combinations lie above the line in the $(\Delta M - \cos\theta_-)$ plane shown in Fig. 1b. An analogous procedure and cut were used to remove misidentified combinations from $D^0 \to K^-\pi^+$ which feed into $D^0 \to \pi^-\pi^+$ (see Fig. 1a). The background due to a long non-gaussian tail in the D^0 mass spectrum in the $K^-\pi^+$ channel was estimated to be less than 3 events and therefore neglected.

Another important source of background arises from the decay $D^0 \to K^-\pi^+\pi^0$. Missing the π^0 and also misidentifying the π^+ as a K^+ can feed events from $K^-\pi^+\pi^0$ into the K^-K^+ channel. However, the width of the D^{*+} peak resulting from misidentified events is 2.5 times larger than for the signal. The shape and normalization of this background were determined by a Monte Carlo study, and then added to the smooth background used during the fitting procedure of the $D^0\pi^+$ invariant mass distribution.

The resultant $D^0\pi^+$ invariant mass plots are shown in Fig. 2. The spectra were fitted with a function which is a sum of a gaussian, to parametrize the signal, and a polynomial times square-root threshold factor, to parametrize the background. The background function for the K^+K^- channel also included the additional reflection contribution described

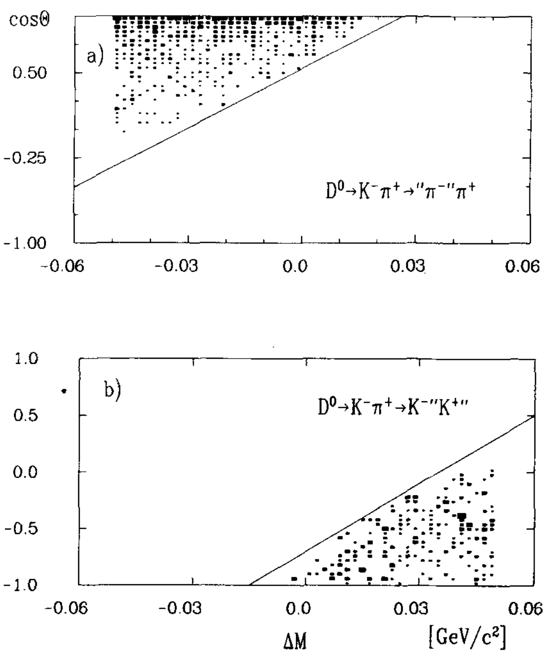

Fig. 1a, b. $\Delta M - \cos\theta_-$ distribution for misidentified events from $D^0 \to K^-\pi^+$ channel **a)** $D^0 \to \pi^-$"π^+", **b)** $D^0 \to K^-$"K^+"

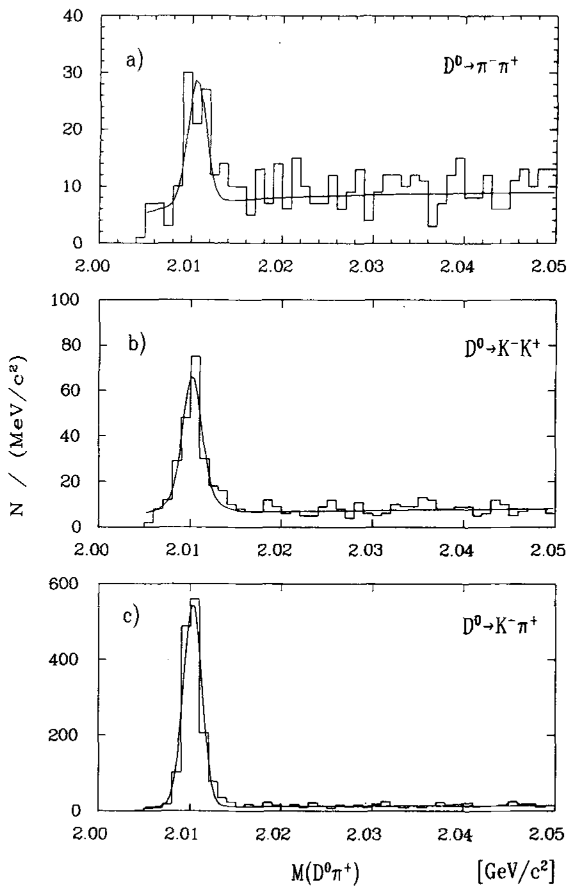

Fig. 2a–c. $D^0\pi^+$ invariant mass distribution for three D^0-decay channels: **a)** $D^0 \to \pi^-\pi^+$, **b)** $D^0 \to K^-K^+$, **c)** $D^0 \to K^-\pi^+$

Table 1. D^0-decays into K^-K^+ and $\pi^-\pi^+$

D^0 decay mode	Number of events	Ratio	ARGUS	MARK III [9, 19]
K^-K^+	131 ± 20	$\frac{BR(D^0 \to K^-K^+)}{BR(D^0 \to K^-\pi^+)}$	$0.10 \pm 0.02 \pm 0.01$	$0.122 \pm 0.018 \pm 0.012$
$\pi^-\pi^+$	57 ± 9	$\frac{BR(D^0 \to \pi^-\pi^+)}{BR(D^0 \to K^-\pi^+)}$	$0.040 \pm 0.007 \pm 0.006$	$0.033 \pm 0.010 \pm 0.006$
$K^-\pi^+$	1350 ± 38	$BR(D^0 \to K^-\pi^+)$		$4.2 \pm 0.4 \pm 0.4$
		$\frac{BR(D^0 \to K^-K^+)}{BR(D^0 \to \pi^-\pi^+)}$	2.5 ± 0.7	3.7 ± 1.4

above. Since the observed signal widths are consistent with the resolution of 1 MeV/c^2 expected from Monte Carlo studies, the width of the gaussian was fixed to this value during the fitting procedure. In Tables 1–3 are summarized the number of fitted events in each channel, and the resulting branching ratios normalized to the Cabibbo-allowed channel $D^0 \to K^-\pi^+$.

Many of the systematic errors in the ratio of branching ratios cancel, since most of the efficiencies, such as track reconstruction and trigger efficiencies, are equal for the Cabibbo-suppressed and Cabibbo-allowed channels. The only factors which contribute are differences in the particle identification efficiencies for the $\Delta M - \cos\theta_-$ plane cut, and losses due to kaon decay. The particle identification efficiency was determined from the data, while the other two were determined by Monte Carlo. The dominant source of the systematic errors is the uncertainty in the background shape of the $D^0\pi^+$ mass spectra.

The decays $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ have been studied by several groups [8, 9, 14, 15]. The most accurate results were obtained by the MARK III collaboration [9], which are included in Table 1. Our ratio of branching ratios for the decays $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ is lower than the MARK III result, but consistent within the large errors.

4 $D^0 \to K^0\bar{K}^0$ and $D^0 \to K_s^0 K_s^0 K_s^0$ decays

The decay $D^0 \to K^0\bar{K}^0$ is interesting because it can occur only through final state interactions (see [17] for a discussion), and thus, if observed, is a clear indicator of their importance.

K_s^0 mesons were reconstructed from $\pi^-\pi^+$ pairs from secondary vertices [13]. The cosine of the angle between the momentum vector of the $\pi^+\pi^-$ system and the direction from the interaction point to the K_s^0 decay vertex was required to be larger than 0.9.

No event was seen in the D^{*+} mass region from the decay $D^0 \to K_s^0 K_s^0$ while there were 282 ± 18 events from the decay $D^0 \to K_s^0\pi^-\pi^+$. Using $BR(D^0 \to K_s^0\pi^-\pi^+) = (3.2 \pm 0.4 \pm 0.4)\%$ [14], we obtain an upper limit of $BR(D^0 \to K^0\bar{K}^0) < 0.11\%$ at the 90% confidence level.

A slightly better limit can be obtained directly from the $K_s^0 K_s^0$ mass distribution, without requiring the D^{*+} reconstruction. This limit and numbers of events in each channel are shown in Table 2. The ratio $BR(D^0 \to \bar{K}^0K^0)/BR(D^0 \to K^-K^+)$ is slightly larger than value recently reported [18] by the E400 collaboration (after scaling the E400 result by a factor of two, to account for $BR(D^0 \to K^0\bar{K}^0) = 2\,BR(D^0 \to K_s^0 K_s^0)$).

Table 2. D^0-decays into $K_s^0 K_s^0 K_s^0$ and $K_s^0 K_s^0$

D^0 decay mode	Number of events	Ratio	ARGUS	Other experiments
$K_s^0 K_s^0 K_s^0$	5.5 ± 2.5	$\frac{BR(D^0 \to K_s^0 K_s^0 K_s^0)}{BR(D^0 \to K_s^0\pi^-\pi^+)}$	$0.034 \pm 0.014 \pm 0.010$	
$K_s^0 K_s^0$	<8	$\frac{BR(D_0 \to \bar{K}^0K^0)}{BR(D^0 \to K^0\pi^-\pi^+)}$	<0.016 at 90% CL	<0.072 at 90% CL [19]
$K_s^0\pi^-\pi^+$	876 ± 29	$BR(D^0 \to K_s^0\pi^-\pi^+)$		$3.2 \pm 0.4 \pm 0.4$ [14]
		$\frac{BR(D^0 \to \bar{K}^0K^0)}{BR(D^0 \to K^-K^+)}$	<0.24 at 90% CL	0.20 ± 0.15 [18]

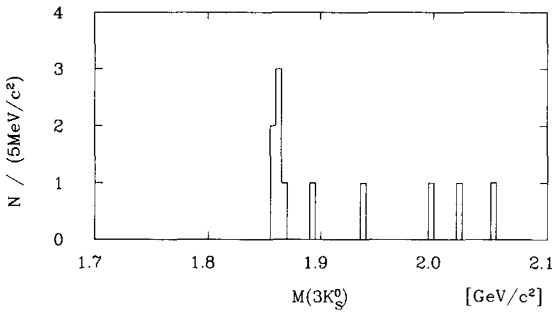

Fig. 3. Invariant mass distribution of $K_s^0 K_s^0 K_s^0$

It is worthwhile to mention that we see a D^0 signal in the $K_s^0 K_s^0 K_s^0$ final state (see Fig. 3). This is the first observation of this channel. The fitted number of events, and the resultant branching ratio for this channel, are also listed in Table 2. The significance of the signal is more than four standard deviations. There is no $\bar{u}$ quark in final state of this channel as in the case for $D^0 \to \bar{K}^0 \phi$, previously observed [20].

Efficiencies for these channels with K_s^0 mesons were determined by Monte Carlo. Uncertainties from this source range from 24% in $BR(D^0 \to K_s^0 K_s^0 K_s^0)$ to 11% in $BR(D^0 \to K_s^0 \pi^- \pi^+)$. This is the main source of systematical uncertainties.

5 $D^0 \to K_s^0 K^- \pi^+$ decay

In Fig. 4, the $D^0 \pi^+$ invariant mass distributions are shown for the decays $D^0 \to K_s^0 K^- \pi^+$ and $D^0 \to K_s^0 \pi^- \pi^+$. Here we required that the scaled momentum of the D^{*+} exceeds 0.6 in order to reduce the large combinatorial background.

Misidentification of a pion as a kaon can feed events from the decay $D^0 \to K_s^0 \pi^- \pi^+$ into the $D^0 \to K_s^0 K^- \pi^+$ channel. However, the resultant mass shift in this case is larger than in two-body D^0 decays, and so misidentified events lie outside the D^0 mass region. For the same reason background due to $K \to \pi$ misidentification in the decay $D^0 \to K_s^0 K^- K^+$ is negligible.

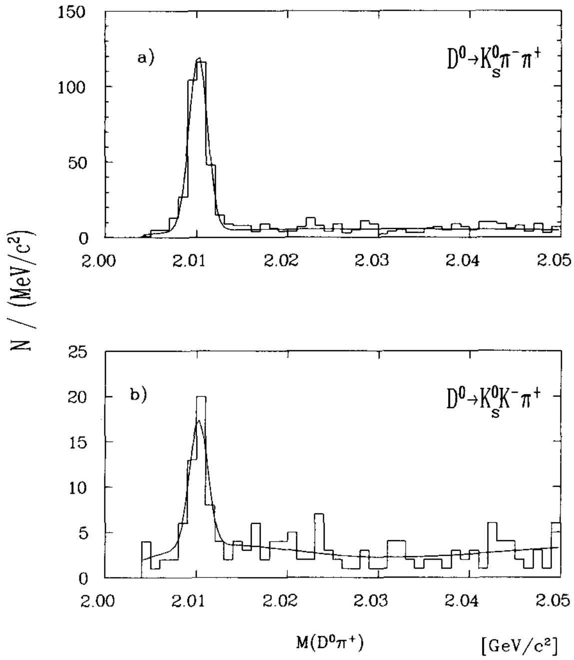

Fig. 4a, b. $D^0 \pi^+$ invariant mass distribution for decay channels a) $D^0 \to K_s^0 \pi^- \pi^+$, and b) $D^0 \to K_s^0 K^- \pi^+$

Missing the π^0, combined with $\pi \to K$ misidentification, can feed events from the decay $D^0 \to K_s^0 \pi^+ \pi^- \pi^0$ into the $D^0 \to K_s^0 K^- \pi^+$ channel. However, the width of the D^{*+} mass spectrum for misidentified events is substantially larger than for the signal. The contribution from this background source was determined by Monte Carlo study, and then added to the smooth background used during the fitting procedure of the $D^0 \pi^+$ invariant mass distribution. The fitted number of events and the ratio $BR(D^0 \to K_s^0 K^- \pi^+)/BR(D^0 \to K_s^0 \pi^- \pi^+)$ are shown in Table 3.

Figure 5 shows the invariant mass distributions for $K_s^0 \pi^+$ and $K^- \pi^+$ combinations in the D^0

Table 3. $D^0 \to K_s^0 K^- \pi^+$ decay

D^0 decay mode	Number of events	Ratio	ARGUS	Other experiments
$K_s^0 K^- \pi^+$	39 ± 7	$\frac{BR(D^0 \to K_s^0 K^- \pi^+)}{BR(D^0 \to K_s^0 \pi^- \pi^+)}$	$0.16 \pm 0.03 \pm 0.02$	0.16 ± 0.07 [15]
$K^{*+} K^-$	15 ± 7	$\frac{BR(D^0 \to K^{*+} K^-)}{BR(D^0 \to K_s^0 \pi^- \pi^+)}$	$0.10 \pm 0.04 \pm 0.02$	0.13 ± 0.09 [19]
$K_s^0 \bar{K}^{*0}$	<5	$\frac{BR(D^0 \to \bar{K}^{*0} K_s^0)}{BR(D^0 \to K_s^0 \pi^- \pi^+)}$	<0.03 at 90% CL	<0.09 at 90% CL [19]
$K_s^0 \pi^- \pi^+$	282 ± 18	$BR(D^0 \to K_s^0 \pi^- \pi^+)$		$3.2 \pm 0.4 \pm 0.4$

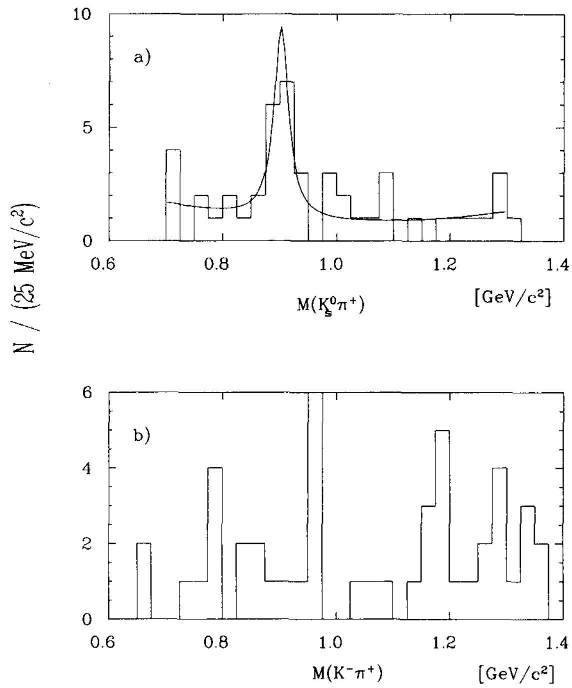

Fig. 5. a) $K_s^0 \pi^+$ and **b)** $K^- \pi^+$ invariant mass distribution for the decay $D^0 \to K_s^0 K^- \pi^+$

$\to K_s^0 K^- \pi^+$ signal from D^{*+} region. Some indication of K^{*+} production can be seen. The ratio of the branching ratio for the decay $D^0 \to K^{*+} K^-$, and the upper limit for $D^0 \to \bar{K}^{*0} K_s^0$, normalized to the $D^0 \to K_s^0 \pi^- \pi^+$ branching ratio are listed in Table 3.

In summary, we have measured branching ratios for the Cabibbo-suppressed decays $D^0 \to \pi^- \pi^+$, $D^0 \to K^- K^+$, $D^0 \to K_s^0 K^- \pi^+$, and $D^0 \to K^{*+} K^-$. We have also obtained upper limits on $\mathrm{BR}(D^0 \to K^0 \bar{K}^0)$ and $\mathrm{BR}(D^0 \to K_s^0 \bar{K}^{*0})$. Our measurements are in agreement with the results obtained in the other experiments but are more precise. We have also observed the Cabibbo-allowed decay $D^0 \to K_s^0 K_s^0 K_s^0$.

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