Search for $D^0 \to \ell^+\ell^-$ decays and for CP violation in $D^+_s \to K_S^0\pi^+$ and $D^+_s \to K_S^0 K^+$ at BELLE

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Abstract. We are reporting on a search for flavour-changing neutral current decays $D^0 \to \mu^+\mu^-$ and $D^0 \to e^+e^-$, and for lepton-flavour violating decays $D^0 \to e^\pm\mu^\mp$, the measurement of $D^+_s \to K_S^0\pi^+$ and $D^+_s \to K_S^0 K^+$ branching fractions, and the search for CP violation in $D^+_s \to K_S^0\pi^+$ and $D^+_s \to K_S^0 K^+$ decays. The analyses are based on $600 \text{ fb}^{-1}$ to $700 \text{ fb}^{-1}$ of data collected in $e^+e^-$ collisions at the centre-of-mass (CM) energy of the $\Upsilon(4S)$ resonance and 60 MeV below by the Belle detector at the KEKB collider.

1. Search for $D^0 \to \ell^+\ell^-$ decays
The flavour-changing neutral current (FCNC) decays $D^0 \to \mu^+\mu^-$ and $D^0 \to e^+e^-$, and for lepton-flavour violating decays $D^0 \to e^\pm\mu^\mp$, the measurement of $D^+_s \to K_S^0\pi^+$ and $D^+_s \to K_S^0 K^+$ branching fractions, and the search for CP violation in $D^+_s \to K_S^0\pi^+$ and $D^+_s \to K_S^0 K^+$ decays. The analyses are based on 600 fb$^{-1}$ to 700 fb$^{-1}$ of data collected in $e^+e^-$ collisions at the centre-of-mass (CM) energy of the $\Upsilon(4S)$ resonance and 60 MeV below by the Belle detector at the KEKB collider.

Using 660 fb$^{-1}$ of data we searched for the decays $D^0 \to \mu^+\mu^-$, $D^0 \to e^+e^-$ and $D^0 \to e^\pm\mu^\mp$. We use $D^0$ mesons from the decays $D^{*+} \to D^0\pi^+$ with a characteristic low momentum pion, since this considerably improves the purity of the reconstructed samples. We normalise the sensitivity of our search to topologically similar $D^0 \to \pi^+\pi^-$ decays; this cancels various systematic uncertainties. The signal efficiencies $\epsilon_{\ell\ell}$ and $\epsilon_{\pi\pi}$ are evaluated using signal Monte Carlo simulation.

In order to avoid biases, a blind analysis technique has been adopted. As the $D^0 \to \ell^+\ell^-$ decays are not expected to be observed at the current sensitivity, we maximise the figure-of-merit, $F = \epsilon_{\ell\ell}/N_{UL}$, where $\epsilon_{\ell\ell}$ is the efficiency for detecting $D^0 \to \ell^+\ell^-$ decays, and $N_{UL}$ is the Poisson average of Feldman-Cousins 90% confidence level upper limits on the number of observed signal events that would be obtained with the expected background and no signal [6].

The background events can be grouped into two categories: (1) a smooth combinatorial background, and (2) a peaking background from the misidentification of $D^0 \to \pi^+\pi^-$ decays. To estimate the number of combinatorial background events in the signal region, the sideband region is used. The peaking background in the signal region due to misidentification of $D^0 \to \pi^+\pi^-$ decays is estimated from the reconstructed $D^0 \to \pi^+\pi^-$ decays found in data
and the misidentification probability measured in data using \( D^{*+} \to D^0 \pi^+_s \), \( D^0 \to K^-\pi^+ \) decays, binned in particle momentum \( p \) and cosine of polar angle.

![Figure 1. The dilepton invariant mass distributions for a) \( D^0 \to \mu^+\mu^- \), b) \( D^0 \to e^+e^- \) and c) \( D^0 \to e^+\mu^\mp \). The dashed vertical lines indicate the optimised signal window. Superimposed on the data (open histograms) are the estimated distribution for combinatorial background (filled histogram), the misidentification of \( D^0 \to \pi^+\pi^- \) (cross-hatched histogram), and the signal if the branching fractions were equal to the 90% confidence level upper limit (single hatched histogram).]

The invariant mass distributions after applying the optimised event selection criteria are shown in Figure 1. In the signal region we find two candidates in the \( D^0 \to \mu^+\mu^- \), zero candidates in the \( D^0 \to e^+e^- \) and three candidates in the \( D^0 \to e^+\mu^\mp \) decay mode; the yields are consistent with the estimated background of \( 3.1 \pm 0.1, 1.7 \pm 0.2 \), and \( 2.6 \pm 0.2 \) events respectively. A binned maximum likelihood fit is used to determine the yield of \( D^0 \to \pi^+\pi^- \) candidates for the normalisation. Finally, the branching fraction upper limits (UL) are calculated using the program pole.f, which extends the Feldman-Cousins method by the inclusion of systematic uncertainties [7]. The upper limits on the branching fractions at the 90% confidence level are found to be \( B(D^0 \to \mu^+\mu^-) < 1.4 \times 10^{-7} \), \( B(D^0 \to e^+e^-) < 7.9 \times 10^{-8} \), and \( B(D^0 \to e^+\mu^\mp) < 2.6 \times 10^{-7} \) [8]. Our results improve the current limits by a factor of 9 for \( D^0 \to \mu^+\mu^- \) decay, by a factor of 15 for \( D^0 \to e^+e^- \) decay and by a factor of 3 for \( D^0 \to e^+\mu^\mp \) decay [9]. In 2008 the CDF collaboration reported a preliminary result on the UL for the \( D^0 \to \mu^+\mu^- \) branching fraction [10]; our result is lower by a factor of 3 and strongly disfavours a leptoquark contribution [5] as the explanation for the anomaly in the measured \( D^+_s \to \mu^+\nu \) width [11].

2. Branching fraction measurement of \( D^{+(s)} \to K^0_S\pi^+ \) and \( D^{+(s)} \to K^0_SK^+ \) decays

Decays of charmed mesons play an important role in understanding the sources of SU(3) flavour symmetry breaking [12]. For \( D^+ \) decays, the branching ratio \( B(D^+ \to \overline{K}^0 K^+)/B(D^+ \to \overline{K}^0 \pi^+) \) deviates from the naive \( \tan^2 \theta_C \) expectation [9], due to the destructive interference between colour-favoured and colour-suppressed amplitudes in \( D^+ \to \overline{K}^0 \pi^+ \) [13]. However, converting experimental measurements of \( D \) decays that include \( K^0_S \) branching ratios to those involving \( K^0 \) or \( \overline{K}^0 \) is not straightforward due to the interference between the doubly Cabibbo-suppressed (DCS) and Cabibbo-favoured (CF) decay modes where the interference phase is unknown [14, 15].

Based on a data sample of 605 fb\(^{-1}\) we measured the \( D^+ \to K^0_S K^+ \) and \( D^+_s \to K^0_S \pi^+ \) branching ratios with respect to the corresponding Cabibbo-favoured modes. The invariant mass distributions of the selected events are shown in Figure 2. The results are \( B(D^+ \to \overline{K}^0 K^+) < 1.4 \times 10^{-7} \) and \( B(D^+_s \to K^0_S K^+ < 2.6 \times 10^{-7} \) [16].
3. Search for CP violation in $D^+_s \to K^0_S \pi^+$ and $D^+_s \to K^0_S K^+$ decays

Another important aspect of such decays is the violation of the combined Charge-conjugation and Parity symmetries (CP). In the SM, the charmed particle processes for which a significant non-vanishing CP violation is expected are singly Cabibbo-suppressed (SCS) decays in which there is both interference between two different decay amplitudes and a strong phase shift from final state interactions. In the SM, CP violation in SCS charmed meson decays is predicted to occur at the level of $\mathcal{O}(0.1\%)$ or lower [17].

Based on a data sample of 673 fb$^{-1}$ we determine the CP violating asymmetry $A_{CP}$ by measuring the signal yield asymmetry $A_{rec} = (N_{rec} - N_{\text{rec}})/(N_{rec} + N_{\text{rec}})$ where $N_{rec}(N_{\text{rec}})$ is the number of reconstructed decays of $D^+_s(D^-_s)$. The measured asymmetry in this equation includes two contributions other than $A_{CP}$. One is the forward-backward asymmetry ($A_{FB}$) due to $\gamma^* - Z^0$ interference in $e^+e^- \to c\bar{c}$ and the other is a detection efficiency asymmetry between positively and negatively charged tracks $A_h^B = (\epsilon^+ - \epsilon^-)/\epsilon^+ + \epsilon^-$, where $\epsilon^+ (\epsilon^-)$ is the efficiency for $K^+(K^-)$ or $\pi^+(\pi^-)$ meson and $h$ denotes $K$ or $\pi$. Since $K^0_S$ mesons are reconstructed from a $\pi^+\pi^-$ pair, there is no detection asymmetry other than $A_h^B$. The signal yield asymmetry can therefore be expressed as $A_{rec} = A_{CP} + A_{FB} + A_h^B$.

To correct for the asymmetries other than $A_{CP}$, we use reconstructed samples of $D^+_s \to \phi\pi^+$ and $D^0 \to K^-\pi^+$ decays and assume that $A_{CP}$ in CF decays is negligibly small compared to $K^0_S K^+/B(D^+ \to K^0_S \pi^+) = 0.1899 \pm 0.0011 \pm 0.0022$ and $B(D^+_s \to K^0_S \pi^+)/B(D^+_s \to K^0_S K^+) = 0.0803 \pm 0.0024 \pm 0.0019$, where the first uncertainties are statistical and the second are systematic [16]. Using the world average values of CF decay rates [9], we obtain the branching fractions $B(D^+ \to K^0_S K^+) = (2.75 \pm 0.08) \times 10^{-3}$ and $B(D^+_s \to K^0_S \pi^+) = (1.20 \pm 0.09) \times 10^{-3}$ where the uncertainties are the sum in quadrature of statistical and systematic errors. These are consistent with the present world averages [9] and are the most precise measurements up to now. The ratio $B(D^+ \to K^0_S K^+)/B(D^+_s \to K^0_S \pi^+) = 2.29 \pm 0.18$ may be due to SU(3) flavour breaking and/or different final-state interactions in $D^+$ and $D^+_s$ decays.

![Figure 2](image_url)
the current experimental sensitivity and that $A_{FB}$ is the same for all charmed mesons. We reconstruct $\phi$ mesons via their $\phi \rightarrow K^+K^-$ decays. The measured asymmetry for $D^+_s \rightarrow \phi\pi^+$ is the sum of $A_{FB}$ and $A_{CP}^s$. Hence one can extract the $A_{CP}$ value for the $K_S^0\pi^+$ final state by subtracting the measured asymmetry for $D^+_s \rightarrow \phi\pi^+$ from that for $D^+_{(s)} \rightarrow K_S^0\pi^+$.

The method for the measurement of $A_{CP}$ in the $K_S^0K^+$ final states is different from that for the $K_S^0\pi^+$ final states. The $A_{FB}$ and $A_{CP}^s$ components in $A_{rec}$ are directly obtained from the $D^+_s \rightarrow \phi\pi^+$ sample, but there is no corresponding large statistics decay mode that can be used to directly measure the $A_{FB}$ and $A_{CP}^s$ components in $A_{rec}$. Thus, to correct the reconstructed asymmetry in the $K_S^0K^+$ final states, we use samples of $D^0 \rightarrow K^-\pi^+$ as well as $D^+_s \rightarrow \phi\pi^+$ decays. The value $A_{rec} - A_{CP}$ includes not only an $A_{CP}$ component but also an $A_{FB}$ component. Since $A_{CP}$ is independent of all kinematic variables, while $A_{FB}$ is an odd function of $\cos\theta_{D_s^{+}}$, we can deduce both by addition/subtraction in bins of $\cos\theta$. Figure 3 shows the results.

![Figure 3. Measured $A_{CP}$ and $A_{FB}$ values for $D_{(s)}^{+} \rightarrow K_{S}^{0}K^{+}$ as a function of $|\cos\theta_{D_{(s)}^{+}}|$. The dashed curves show the leading-order prediction for $A_{FB}^{s}$.](image)

No evidence for $CP$ violation has been observed [18]. Our results are $A_{CP}^{D_{s}^{+} \rightarrow K_{S}^{0}\pi^{+}} = (-0.71 \pm 0.19 \pm 0.20)\%$, $A_{CP}^{D_{s}^{+} \rightarrow K_{S}^{0}\pi^{+}} = (+5.45 \pm 2.50 \pm 0.33)\%$, $A_{CP}^{D_{s}^{+} \rightarrow K_{S}^{0}K^{+}} = (-0.16 \pm 0.58 \pm 0.25)\%$, and $A_{CP}^{D_{s}^{+} \rightarrow K_{S}^{0}K^{+}} = (+0.12 \pm 0.36 \pm 0.22)\%$. They are consistent with the SM predictions and provide the most stringent constraints up to now on models beyond the SM [14].

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