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Measurements of Wrong-Sign Decays, Mixing and CP Violation in D^0 Decays at Belle

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We report on a search for mixing and CP violation in the system of D^0 mesons and on the measurement of the wrong-sign D^0 decay rates at Belle. Using $D^0 \to K^+\pi^-$ decays we obtain the following 95% C.L. limits on mixing parameters: $x'^2 < 0.81 \cdot 10^{-3}$, $-0.0082 < y' < 0.016$. The search for D^0 mixing in $D^0 \to K^+ e^- \overline{\nu}_e$ mode gives $(x^2+y^2)/2 < 1.2 \cdot 10^{-3}$ at 95% C.L. The measured wrong-sign decay rates are:
$\mathscr{B}(D^0 \to K^+\pi^-)/\mathscr{B}(D^0 \to K^-\pi^+) = (3.71 \pm 0.18(\text{stat})) \cdot 10^{-3}$,
$\mathscr{B}(D^0 \to K^+\pi^-\pi^0)/\mathscr{B}(D^0 \to K^-\pi^+\pi^0) = (2.29 \pm 0.15(\text{stat})^{+0.13}_{-0.09}(\text{syst})) \cdot 10^{-3}$ and
$\mathscr{B}(D^0 \to K^+\pi^-\pi^+\pi^-)/\mathscr{B}(D^0 \to K^-\pi^+\pi^-\pi^+) = (3.20 \pm 0.18(\text{stat})^{+0.18}_{-0.13}(\text{syst})) \cdot 10^{-3}$.
We find no CP asymmetry in these decays.

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1. Introduction

D^0 mesons can decay hadronically through the Cabibbo favored mechanism into the right-sign (RS) final states ($K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^-\pi^+$, ...). At considerably lower rate also wrong-sign (WS) final states are possible ($K^+\pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^+\pi^-$, ...). These can occur either through doubly Cabibbo suppressed decays (DCSD) or through *e.g.* $D^0-\overline{D}^0$ mixing ($D^0\to\overline{D}^0\to K^+\pi^-$). Semileptonic decays resulting in a WS final state can only proceed via mixing ($D^0\to\overline{D}^0\to K^+e^-\overline{\nu_e}$).

The phenomenon of mixing has not yet been observed in the $D^0-\overline{D}^0$ system. The parameters used to characterize $D^0-\overline{D}^0$ mixing are $x=\Delta m/\overline{\Gamma}$ and $y=\Delta\Gamma/2\overline{\Gamma}$, where Δm and $\Delta\Gamma$ are the differences in mass and decay width between the two neutral charmed meson mass eigenstates, and $\overline{\Gamma}$ is the mean decay width. The mixing rate within the Standard Model is expected to be small [1]: the largest predicted values, including the impact of long distance dynamics, are of the order $x\lesssim y\sim 10^{-3}-10^{-2}$.

Measurements described in this paper were performed using the data collected by the Belle detector [2], positioned at the interaction point of the KEKB asymmetric-energy e^+e^- collider [3], with the center-of-mass energy of 10.58 GeV.

2. $D^0\to K^+\pi^-$ mixing search

To perform the search, we use $D^{*+}\to D^0\pi_s^+$ decays which enable a suppression of combinatorial background, and tagging of WS and RS decays using the charge of the slow pion π_s.

The observables to extract the signal of $D^0\to K^+\pi^-$ decays are the mass of the D^0 candidate $M(K\pi)=\sqrt{(E_K+E_\pi)^2-(\vec{p}_K+\vec{p}_\pi)^2}$ and the released energy $Q=M(\pi_sK\pi)-M(K\pi)-m_\pi$, where m_π is the nominal mass of the charged pion. We demand the momentum of the D^{*+} candidate in the e^+e^- center-of-mass (CM) frame to be greater than 2.5 GeV in order to reject D^{*+} candidates from B decays. To eliminate background from double misidentification we reject D^0 candidates with $|M(K\pi(\text{swapped}))-\mathrm{m}_{\mathrm{D}^0}|<28$ MeV, $M(K\pi(\text{swapped}))$ being the mass calculated by swapping mass assignments of K^+ and π^- candidates.

The background is divided into 4 categories: a) correct D^0 candidate with a random π_s candidate, b) 3- or more-body D^0 decays, c) D^+/D_s^+ decays, d) combinatorial. The $(M(K\pi),Q)$ shape of each category of background is parametrised using Monte Carlo (MC) simulation.

In the 3σ $M(K\pi)$ and Q region the fit yields 845 ± 40 WS and $227\,721\pm497$ RS events, their ratio being $R_{WS}^{K\pi}=(0.371\pm0.018)\%$. Signal to background ratio in the WS sample in this region is $S/N=0.9$. $M(K\pi)$ and Q dependent S/N ratio is extracted to be used in the proper decay time fit. In hadronic WS decays one has to distinguish between DCSD and mixing via the D^0 proper decay time distribution:

$$\frac{dN_{WS}^{\text{hadronic}}}{dt}\propto[R_D+\sqrt{R_D}y't+\frac{1}{2}R_Mt^2]e^{-t}, \tag{2.1}$$

where $R_M=(x'^2+y'^2)/2$ and $x'=x\cos\delta+y\cos\delta$, $y'=x\cos\delta-y\cos\delta$. The phase δ is the mode dependent strong phase difference between RS and WS decays. The first term is due to DCSD, the third due to mixing and the second is the interference term between mixing and DCSD.

D^0 proper decay time is calculated from D^0 flight distance and its momentum. The D^0 decay vertex is obtained by fitting the daughter K/π tracks. The D^0 production vertex is taken as the intersection of the D^0 momentum vector with the interaction profile region.

We obtain R_D, x'^2 and y' (2.1) via an unbinned maximum likelihood fit to the WS decay-time distribution. The fitting procedure and other details of the analysis can be found in [4]. The resulting values on a data sample with integrated luminosity of 90 fb^{-1} are: $R_D = (0.287 \pm 0.037)\%$, $x'^2 = (-0.153^{+0.08}_{-0.10})\%$, $y' = (2.54^{+1.11}_{-1.02})\%$, assuming no CP violation. As the latter two are consistent with zero, we find the 95% C.L. region for the mixing parameters by performing a toy MC study : $0.0027 < R_D < 0.004$, $x'^2 < 0.81 \cdot 10^{-3}$, $-0.0082 < y' < 0.016$.

To test for CP violation we perform the fit separately in D^0 and $\overline{D}^0$ samples, obtaining R_D^+, $(x'^+)^2$ and y'^+ for the D^0 and R_D^-, $(x'^-)^2$ and y'^- for $\overline{D}^0$ sample. We calculate $R_M^\pm = ((x'^\pm)^2 + (y'^\pm)^2)/2$ and measure asymmetries $A_D = (R_D^+ - R_D^-)/(R_D^+ + R_D^-)$ and $A_M = (R_M^+ - R_M^-)/(R_M^+ + R_M^-)$. Both are consistent with zero, the 95% C.L. being $-0.25 < A_D < 0.11$ and $-0.99 < A_M < 1.00$.

3. $D^0 \to K^+ e^- \nu_e$ mixing search

The variable used to extract the signal of the semileptonic $D^0 \to Ke\nu$ decays is $\Delta M = M(\pi_s Ke\nu) - M(Ke\nu)$. The neutrino is reconstructed exploiting the detector hermeticity and kinematic constraints. Details of the reconstruction can be found in [5]. To suppress D mesons from B decays we reject candidates with K-e CM momentum lower than 2.0 GeV. We also reject candidates with $M(Ke) > 1.82$ GeV to suppress the background from $D^0 \to K^-\pi^+$ decays.

The remaining backgrounds for both RS and WS decays consist mainly of combinatorial background and are modelled using the data. For the RS combinatorial background we use candidates with the unphysical charge combinations $\pi_s^+ K^- e^-$ and $\pi_s^+ K^+ e^+$. In the WS sample this background is modelled by combining π_s^+ and $(K^- + e^+)$ candidates from different events. The charge correlated background (1.6% in the RS, 2.0% in the WS sample) is described using the MC.

We increase the sensitivity to $D^0 - \overline{D}^0$ mixing by exploiting the measurement of the D^0 proper decay time (the distribution of mixed events is $dN_{\mathrm{mix}}/dt \propto t^2 e^{-t/\tau_D}$). The interaction region of the KEKB accelerator is narrowest in the vertical (y) direction, and hence the dimensionless proper decay time t_y is calculated as $t_y = \frac{m_{D^0}}{c\tau_{D^0}} \frac{y_{\mathrm{vtx}} - y_{\mathrm{IP}}}{p_y}$, where p_y is the y component of the D^0 candidate's momentum and y_{vtx} and y_{IP} are the y coordinates of the reconstructed K-e vertex and of the interaction point, respectively.

To extract the result we select the region $1.0 < t_y < 10.0$ and divide it into 6 intervals. Using a binned maximum likelihood fit to ΔM we extract the number of RS and WS signal events in each of these intervals. We obtain the time-integrated mixing probability ratio in the i-th t_y interval, $R_M^i = N_{\mathrm{WS}}^i / N_{\mathrm{RS}}^i \times \varepsilon_{\mathrm{RS}}^i / \varepsilon_{\mathrm{WS}}^i$, by multiplying the ratio of WS to RS signal events in each interval by the t_y efficiency ratio. We quote the result of the χ^2 fit of a constant to these 6 values as our final time integrated mixing rate R_M, which is in the limit $x, y \ll 1$ equal to $(x^2 + y^2)/2$. The result of the measurement, performed on a data sample with integrated luminosity of 253 fb^{-1}, is consistent with zero, $R_M = (0.20 \pm 0.47(\mathrm{stat}) \pm 0.14(\mathrm{syst})) \cdot 10^{-3}$. The 95% C.L. upper limit is $R_M < 1.2 \cdot 10^{-3}$.

PoS(HEP2005)224

4. $D^0 \to K^+\pi^-\pi^0$ and $D^0 \to K^+\pi^-\pi^+\pi^-$ WS rates

Similarly to the mixing search in $D^0 \to K^+\pi^-$, the variables used to extract the signal are $M(K\pi\pi^0)$, $Q = M(\pi_s K\pi\pi^0) - M(K\pi\pi^0) - m_\pi$ and $M(K3\pi)$, $Q = M(\pi_s K3\pi) - M(K3\pi) - m_\pi$.To eliminate candidates from B decays we reject D^{*+} candidates with CM momentum lower than 2.5 GeV. To eliminate doubly misidentified candidates we reject candidates with $M(K\pi\pi^0(\text{swapped}))$ in the range 1.78-1.90 GeV and candidates with $|M(K3\pi(\text{swapped})) - \mathrm{m_{D^0}}| < 20$ MeV.

The background is divided into: a) random π_s with correct D^0 candidate, b) other charm background, c) uds background, and in $D \to K3\pi$ also d) background with swapped π_s and π from D^0 decay. Their shapes are described by empirical functions fitted to distributions of MC simulated events. The details of the analysis can be found in [6].

The number of signal events in the RS and WS samples are obtained from a binned maximum likelihood fit to M-Q distribution: $N_{RS}^{K\pi\pi^0} = (8.683 \pm 0.002) \cdot 10^5$, $N_{WS}^{K\pi\pi^0} = 1978 \pm 104$; $N_{RS}^{K3\pi} = (5.259 \pm 0.002) \cdot 10^5$, $N_{WS}^{K3\pi} = 1721 \pm 75$. To calculate R_{WS} we have to account for possibly different reconstruction efficiencies for RS and WS signal events (as a consequence of different resonant structures in RS and WS decays). This is achieved by estimating the simulated efficiency in bins of $(M^2_{K\pi}, M^2_{\pi\pi^0})$ for $K\pi\pi^0$ and in five-dimensional space comprised of the invariant mass squared for various K,π combinations for $K3\pi$, and convolving the efficiency distributions with the observed distribution of reconstructed events in this space. The resulting WS to RS ratios on a data sample with integrated luminosity of 281 fb^{-2} are: $R_{WS}^{K\pi\pi^0} = (2.29 \pm 0.15(\text{stat})^{+0.13}_{-0.09}(\text{syst})) \cdot 10^{-3}$ and $R_{WS}^{K3\pi} = (3.20 \pm 0.18(\text{stat})^{+0.18}_{-0.13}(\text{syst})) \cdot 10^{-3}$. The ratios of reconstruction efficiencies, averaged over the phase space, are: $< \varepsilon_{RS} > / < \varepsilon_{WS} > = 1.01 \pm 0.05$ for $D^0 \to K\pi\pi^0$ and 0.98 ± 0.04 for $D^0 \to K3\pi$.

To check for CP asymmetry we measure R_{WS} separately for D^0 and $\overline{D}^0$ samples and calculate asymmetry $A_{CP} = (R_{WS}(D^0) - R_{WS}(\overline{D}^0))/(R_{WS}(D^0) + R_{WS}(\overline{D}^0)$. Asymmetries in both decay modes are consistent with zero: $A_{CP}^{K\pi\pi^0} = -0.006 \pm 0.053$, $A_{CP}^{K3\pi} = -0.018 \pm 0.044$.

References

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