$D^0$ mixing at Belle

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Abstract. The present paper reports on the evidence for $D^0$–$\bar{D}^0$ mixing. We searched for mixing in two processes using 540 fb$^{-1}$ of data recorded by the Belle detector at the KEKB $e^+e^-$ collider. In the first case, we measured the apparent lifetime for $D^0$ meson decaying to $CP$ eigenstates $K^+K^-$ or $\pi^+\pi^-$, and the lifetime in the $D^0$ decays to $K^−\pi^+$. From the difference of the two lifetimes, the mixing parameter $y_{CP}$ is found to be 3.2 standard deviations from zero. In the second measurement, we analyzed the time dependent Dalitz plot for the $D^0\rightarrow K^0_s\pi^+\pi^-$ decays, from which the mixing parameters $x$ and $y$ are determined. We also searched for a $CP$ asymmetry between $D^0$ and $\bar{D}^0$ decays, and found no evidence for it.

1. Introduction

The phenomenon of particle and anti-particle mixing has been observed in several systems of neutral mesons, $K^0$, $B^0$, and most recently $B^0_s$ mesons. Mixing is also possible in the $D^0$-meson system, but has not been previously observed.

The time evolution of a $D^0$ or $\bar{D}^0$ depends on the mixing parameters $x = (M_1 - M_2)/\Gamma$ and $y = (\Gamma_1 - \Gamma_2)/2\Gamma$, where $M_{1,2}$ and $\Gamma_{1,2}$ are the masses and widths, respectively, of the mass eigenstates, and $\Gamma = (\Gamma_1 + \Gamma_2)/2$. For no mixing, $x = y = 0$. Within the Standard Model (SM), predictions for $x$ and $y$ are dominated by difficult non-perturbative calculations. The largest predictions are $|x|, |y| \sim O(10^{-2})$. Loop diagrams including new, as-yet-unobserved particles could significantly affect the values of $x$ and $y$; several predictions are around a few percent. $CP$-violating effects in $D$-mixing in excess of the very small SM prediction would be a clear signal of new physics.

Both semileptonic and hadronic $D^0$ decays have been used to constrain $x$ and $y$. In order to tag the flavour at production, the $D^0$ meson is usually reconstructed in the decay\footnote{Charge conjugate modes are implied unless explicitly stated otherwise.} $D^{*+} \rightarrow D^0\pi^+_s$, where the charge of a characteristic slow pion $\pi_s$ tags the initial $D^0$ flavour. Usually also the $D^0$ proper decay time is measured, since the decay time distribution of mixed events depends on the mixing parameters $x$ and $y$ and differs from that of not-mixed events. The proper decay time of an event is determined from the distance between the production and the decay vertex. The decay vertex is obtained from $D^0$ daughter tracks, refitted to originate from a common point. The production vertex is found by constraining the $D^0$ momentum vector to originate from the $e^+e^-$ interaction region. The proper decay time resolution is on average equal to one half of the $D^0$ lifetime.

The present measurements are based on 540 fb$^{-1}$ of data accumulated with the Belle detector at the $\Upsilon(4S)$ resonance.
2. Decays to CP eigenstates $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$

In the measurement of the apparent lifetime of the decays to CP eigenstates $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ [1], the mixing parameter

$$y_{CP} = \frac{\tau(K^-\pi^+)}{\tau(K^+K^-)} - 1,$$

is determined, where $\tau(K^+K^-)$ and $\tau(K^-\pi^+)$ are the lifetimes of $D^0 \rightarrow K^+K^-$ (or $\pi^+\pi^-$) and $D^0 \rightarrow K^-\pi^+$ decays, respectively. It can be shown that $y_{CP} = y \cos \phi - \frac{1}{2} A_M x \sin \phi$ [2], where $A_M$ and $\phi$ are CP violation parameters. If CP is conserved, $A_M = 0$ and $y_{CP} = y$.

In addition, a search for CP violation was carried out by measuring the quantity

$$A_T = \frac{\tau(T^0 \rightarrow K^-K^+) - \tau(D^0 \rightarrow K^+K^-)}{\tau(D^0 \rightarrow K^-K^+) + \tau(D^0 \rightarrow K^+K^-)};$$

this observable is equal to $A_T = \frac{1}{2} A_M x \cos \phi - x \sin \phi$ [2].

The following decay sequence was reconstructed: $D^{*+} \rightarrow D^0\pi^+$, followed by $D^0 \rightarrow K^+K^-$, $K^-\pi^+$ or $\pi^+\pi^-$. A $D^{*+}$ momentum greater than 2.5 GeV/c (in the CM) was required to reject $B$-mesons produced in $B$-meson decays and to suppress combinatorial background. The proper decay time of the $D^0$ candidate was then calculated from the projection of the vector joining the two vertices, $\vec{L}$, onto the $D^0$ momentum vector, $t = m_{D^0}\vec{L}/p^2$, where $m_{D^0}$ is the nominal $D^0$ mass. The decay time uncertainty $\sigma_t$ was evaluated event-by-event from the covariance matrices of the production and decay vertices.

Candidate $D^0$ mesons were selected using two kinematic observables: the invariant mass $M$ of the $D^0$ decay products and the energy $q = (M_{D^0} - M - m_\pi)c^2$, released in the $D^{*+}$ decay. Here $M_{D^0}$ is the invariant mass of the $D^0\pi_\pi$ combination and $m_\pi$ is the $\pi^+$ mass.

Selection criteria were chosen to minimize the expected statistical error of $y_{CP}$, $|M - m_{D^0}|/\sigma_M < 2.3$, $|q - (m_{D^{*+}} - m_{D^0} - m_\pi)c^2| < 0.80$ MeV, and $\sigma_t < 370$ fs. Here the invariant mass resolution $\sigma_M$ varies from 5.5 MeV/c^2 to 6.8 MeV/c^2, depending on the decay channel. In the final sample, we found $111 \times 10^3$ $K^+K^-$, $1.22 \times 10^6$ $K^-\pi^+$, and $49 \times 10^3$ $\pi^+\pi^-$ signal events, with purities of 98%, 99%, and 92%, respectively.

The relative lifetime difference $y_{CP}$ was determined from $D^0 \rightarrow K^+K^-$, $K^-\pi^+$, and $\pi^+\pi^-$ decay time distributions by performing a simultaneous binned maximum likelihood fit to the three samples. Each distribution was assumed to be a sum of signal and background contributions, with the signal contribution being a convolution of an exponential and a detector resolution function. The resolution function was constructed from the normalized distribution of the decay time uncertainties $\sigma_t$ [1]. The background was parameterized assuming two lifetime components: an exponential and a $\delta$ function, each convolved with corresponding resolution functions. Separate background parameters for each final state were determined by fits to the $t$ distributions of events in $M$ sidebands.

The fitted lifetime of $D^0$ mesons in the $K^-\pi^+$ final state, $\tau_{D^0} = (408.7 \pm 0.6$ (stat.)) fs, is in good agreement with the current world average [3]. The relative apparent lifetime difference between decays to CP-even eigenstates and the $K^-\pi^+$ final state is found to be

$$y_{CP} = (1.31 \pm 0.32(\text{stat.}) \pm 0.25(\text{syst.}))\%.$$

Combining the errors in quadrature, this result is 3.2 standard deviations from zero and represents the first experimental evidence for the $D$-mixing, regardless of possible CP violation.

We also searched for CP violation by separately measuring decay times of $D^0$ and $\bar{D}^0$ mesons in CP-even final states. The asymmetry was found to be consistent with zero, $A_T = (0.01 \pm 0.30(\text{stat.}) \pm 0.15(\text{syst.}))\%$. 

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3. Time-dependent Dalitz analysis of $D^0 \rightarrow K_s^0 \pi^+ \pi^-$

A measurement of mixing parameters in the self-conjugate decays $D^0 \rightarrow K_s^0 \pi^+ \pi^-$ was performed using a time-dependent Dalitz plot analysis [4]. The time dependence of the $K_s^0 \pi^+ \pi^-$ Dalitz plot distribution allows one to measure $x$ and $y$ directly. This method was developed by CLEO [5] using 9.0 fb$^{-1}$.

The decay amplitude at time $t$ of an initially produced $D^0$ can be expressed as

$$\mathcal{M}(m_2^2, m_+^2, t) = A(m_2^2, m_+^2) \frac{e_1(t) + e_2(t)}{2} + \frac{2}{p} \mathcal{A}(m_2^2, m_+^2) \frac{e_1(t) - e_2(t)}{2}$$

(4)

where $\mathcal{A}(\mathcal{A})$ is the decay amplitude for $D^0(\overline{D}^0)$ as a function of the invariant masses squared, $m_2^2 = m(K_s, \pi^\pm)^2$; an analogous expression can be derived for an initially produced $\overline{D}^0$.

The time dependence is contained in the terms $e_{1,2}(t) = \exp[-i(m_{1,2} - i\Gamma_{1,2}/2)t]$. Upon squaring $\mathcal{M}$, one obtains decay rates containing terms $\exp(-\Gamma t) \cos(x\Gamma t)$, $\exp(-\Gamma t) \sin(x\Gamma t)$ and $\exp[-(1 \pm y)\Gamma t]$.

The overall decay amplitude $\mathcal{A}$ can be expressed as a sum of quasi-two-body amplitudes $\mathcal{A}_r$ and a constant non-resonant term (subscript NR):

$$\mathcal{A}(m_2^2, m_+^2) = \sum_r a_re^{i\phi_r} \mathcal{A}_r(m_2^2, m_+^2) + a_{NR}e^{i\phi_{NR}}$$

(5)

The functions $\mathcal{A}_r$ are products of Blatt-Weisskopf form factors and relativistic Breit-Wigner functions [6].

The $K_s^0$ was reconstructed in the decay to the $\pi^+ \pi^-$ final state; an invariant mass within $\pm 10$ MeV of $m_{K_s^0}$ and a common vertex separated from the interaction region were required. The $D^0$ decay point was constructed from charged pion tracks only and the production point was obtained from the intersection of the $D^0$ momentum vector with the $e^+e^-$ interaction region.

The signal and background yields were determined from a two-dimensional fit to the variables $M \equiv m_{K_s^0\pi^\pm}$ and $Q \equiv m_{K_s^0\pi^\pm} - m_{K^0_s\pi^\pm}$. In the signal region, defined as $3\sigma$ intervals in $M$ and $Q$, $534 \times 10^3$ signal events were found, with background fractions of 1% and 4% for the random $\pi_s$ and combinatorial backgrounds, respectively.

For the events in the signal region, a simultaneous unbinned likelihood fit to the Dalitz plot variables $m_2^2$ and $m_+^2$, and the decay time $t$ was performed. The free parameters in the fit were $x$, $y$, $\tau_{D^0}$, the timing resolution parameters of the signal, and the Dalitz plot resonance parameters $a_r(NR)$ and $\phi_r(NR)$. The resonance model assumed 18 quasi-two-body resonances; masses and widths were taken from world averages.

The fitted $D^0$ lifetime $\tau_{D^0} = 409.9 \pm 1.0$ fs is consistent with the world average [3]. Assuming negligible CP violation, we measure $x = (0.80 \pm 0.29^{+0.09+0.10}_{-0.07-0.14})\%$ and $y = (0.33 \pm 0.24^{+0.08+0.06}_{-0.12-0.08})\%$; the errors are statistical, experimental systematic, and systematic due to the Dalitz decay model, respectively. The largest contributions to the systematic uncertainty of the result are found to arise from modeling the Dalitz plot density and from the fit to the decay-time distribution. The result for the mixing parameter $x$ represents the most stringent limit on this parameter obtained up to now. If no assumption is made on CP conservation, a fit of the CP violation parameters yields $|q/p| = 0.86^{+0.30+0.06}_{-0.29-0.06} \pm 0.08$ and $\arg(q/p) = (-14^{+16+5+2}_{-18-3-4})^\circ$.

References

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