D^0 mixing and search for CPV at Belle

M. Starič (for the Belle collaboration)[1]
[1]J. Stefan Institute, Ljubljana, Slovenia

Introduction

Particle-antiparticle mixing occurs through weak interactions and gives rise to two different mass eigenstates: $|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$, where p and q are complex coefficients satisfying $|p|^2 + |q|^2 = 1$. The time evolution of the flavor eigenstates, D^0 or $\overline{D}^0$, 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, $x = y = 0$, and for no CP violation (CPV), $q/p = 1$. Within the Standard Model (SM), predictions for x and y are dominated by difficult non-perturbative calculations. The largest predictions are $|x|,\ |y| \sim \mathcal{O}(10^{-2})$. 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^0 mixing (indirect CPV) or decays (direct CPV) in excess of the very small SM predictions would be a clear signal of new physics.

We report here on the measurements in several decay modes: wrong-sign decays to $K^+\pi^-$ final state, decays to CP eigenstates K^+K^-, $\pi^+\pi^-$ and ϕK_s^0, and decays to self-conjugate final state $K_s^0\pi^+\pi^-$. In order to tag the flavour at the production the D^0 meson is usually reconstructed in the decay[1] $D^{*+} \to D^0\pi_s^+$, where the charge of a characteristic slow pion π_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 unmixed 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 trajectory to originate from the e^+e^- interaction region. The proper decay time resolution is typically equal to a half of the D^0 lifetime.

The measurements are performed at $\Upsilon(4S)$ resonance. To reject D^{*+} mesons coming from the decays of B mesons and to reduce background the requirement on the minimal D^{*+} or D^0 momentum in the e^+e^- center-of-mass frame is applied at about 2.5 GeV/c.

Wrong-sign decays $K^+\pi^-$

Wrong-sign (WS) final state can be reached either via doubly Cabibbo suppressed (DCS) decay or via mixing, followed by the Cabibbo favored (CF) decay. The proper decay time distribution of WS events, assuming negligible CPV, is expressed as:

$$\frac{dN}{dt} \propto [R_D + y'\sqrt{R_D}(\Gamma t) + \frac{x'^2 + y'^2}{4}(\Gamma t)^2]e^{-\Gamma t}\ , \quad (1)$$

where R_D is the ratio of DCS and CF decay rates, and $x' = x\cos\delta + y\sin\delta$ and $y' = y\cos\delta - x\sin\delta$ are the mixing parameters, rotated by the barely known strong phase δ. To search for CPV, one fits Eq. 1 to D^0 and $\overline{D}^0$ data samples separately; the resulting $R_D^\pm,\ x'^{2\pm}$ and $y'^\pm$, if different for D^0 (+) and $\overline{D}^0$ (-), are signal for CPV. The non-zero asymmetry in DCS/CF decay rate ratio, $A_D = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-}$, signals CPV in DCS decays; CPV in mixing ($|q/p| \neq 1$) and in the interference of decays with and without mixing ($\phi \equiv \arg(q/p) \neq 0$) can be searched by solving four equations:

$$x'^\pm = (1 \pm \frac{1}{2}A_M)\cdot(x'\cos\phi \pm y'\sin\phi)\ ,$$
$$y'^\pm = (1 \pm \frac{1}{2}A_M)\cdot(y'\cos\phi \mp x'\sin\phi)\ ,$$

for four unknowns x', y', ϕ and $|q/p| = 1 + \frac{1}{2}A_M$.

By using 400 fb^{-1} of data collected with the Belle detector at or near $\Upsilon(4S)$ resonance we measured $x'^2 = (0.18^{+0.21}_{-0.23}) \times 10^{-3}$ and $y' = (0.6^{+4.0}_{-3.9}) \times 10^{-3}$ [1]. Although both results are consistent with zero the non-mixing point is found to be outside the 95% confidence level region, if CP is assumed to be conserved (Fig. 1).

We searched also for CPV; we found the parameters to be consistent with zero: $A_D = (2.3 \pm 4.7)\%$, $A_M = 0.67 \pm 1.2$ and $|\phi| = 0.16 \pm 0.44$.

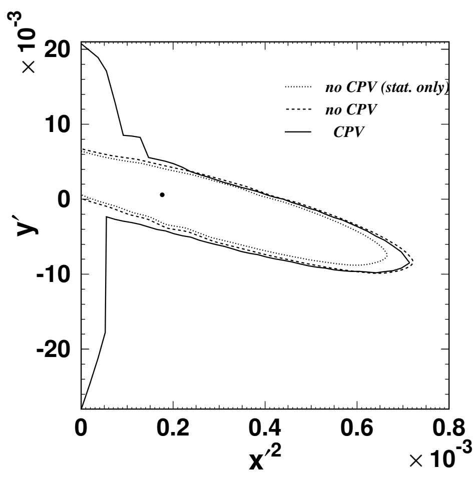

Figure 1: 95% C.L. regions for (x'^2,y').

[1]Charge conjugate modes are implied unless explicitly stated otherwise.

Decays to CP-even eigenstates K^+K^-, $\pi^+\pi^-$

One of the manifestations of mixing is the lifetime difference between decays to CP and flavor eigenstates. The usual way is to measure the relative lifetime difference to $K^-\pi^+$ final state, defined as:

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

which is in the limit of CP conservation equal to mixing parameter y.

If CP is not conserved, $y_{CP} = y\cos\phi - \frac{1}{2}A_M x \sin\phi$; also the lifetimes of D^0 and $\overline{D}^0$ decaying to the same CP-eigenstate differ. The CP violating asymmetry in lifetimes is defined as:

$$A_\Gamma = \frac{\tau(\overline{D}^0 \to K^-K^+) - \tau(D^0 \to K^+K^-)}{\tau(\overline{D}^0 \to K^-K^+) + \tau(D^0 \to K^+K^-)} \, ,$$

which equals to $A_\Gamma = \frac{1}{2}A_M y\cos\phi - x\sin\phi$. By measuring the time-integrated decay rate asymmetry,

$$A^f_{CP} = \frac{\mathcal{B}(D^0 \to f) - \mathcal{B}(\bar{D}^0 \to \bar{f})}{\mathcal{B}(D^0 \to f) + \mathcal{B}(\bar{D}^0 \to \bar{f})} \, ,$$

one can search also for the direct CPV.

We performed the measurements of y_{CP} and A_Γ [2], and A^{KK}_{CP} and $A^{\pi\pi}_{CP}$ [3] using 540 fb^{-1} of data from the Belle detector. Data samples consisted of 110×10^3 K^+K^-, 1.2×10^6 $K^-\pi^+$ and 50×10^3 $\pi^+\pi^-$ signal events passed the final selection criteria.

The relative lifetime difference y_{CP} was determined from $D^0 \to K^+K^-$, $K^-\pi^+$, 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 σ_t [2]. The background was parametrized assuming two lifetime components: an exponential and a δ 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 D^0 mass sidebands.

The fitted lifetime of D^0 mesons in the $K^-\pi^+$ final state, $\tau_{D^0} = (408.7 \pm 0.6 \ (\text{stat.}))$ fs, is in good agreement with the world average. 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. The effect is presented visually in Fig. 2

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

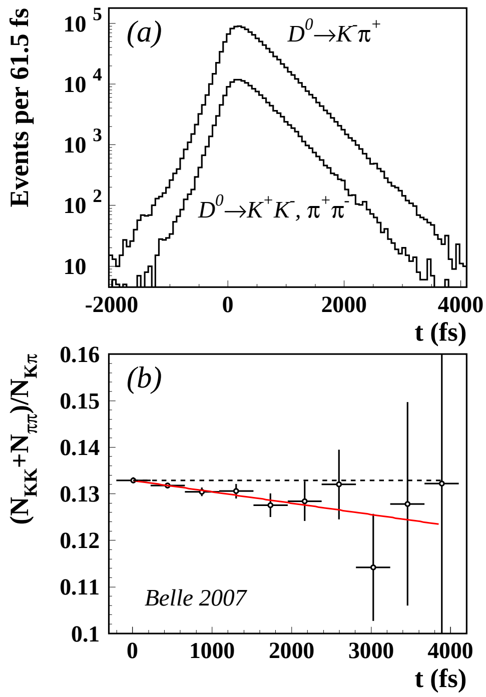

Figure 2: Decay time distributions (a) and their ratio (b). The solid line is a fit to the data points.

By measuring the time-integrated decay rate asymmetry A_{CP} we searched for the direct CPV [3]. We found $A^{KK}_{CP} = (-0.43 \pm 0.30 \pm 0.11)\%$ and $A^{\pi\pi}_{CP} = (+0.43 \pm 0.52 \pm 0.12)\%$; the asymmetries are consistent with zero.

Decays to CP-odd eigenstate ϕK^0_s

Assuming no CPV, the time dependent decay rate of $D^0 \to K^+K^-K^0_s$ can be expressed as [4]:

$$\frac{dN}{dt} \propto a_1(s_0)e^{-\frac{t}{\tau}(1+y)} + a_2(s_0)e^{-\frac{t}{\tau}(1-y)} \, ,$$

where a_1 and a_2 represent the CP-even and CP-odd contributions of the decay amplitude as the function of the Dalitz variable $s_0 \equiv M^2_{KK}$, where M_{KK} is the invariant mass of the two kaons. The mixing parameter y_{CP} can be determined by measuring effective lifetimes in the peak region ($\tau_{\rm ON}$) and in the sideband ($\tau_{\rm OFF}$), as shown in Fig. 3,

$$y_{CP} = \frac{1}{f_{\rm ON} - f_{\rm OFF}} \cdot \frac{\tau_{\rm ON} - \tau_{\rm OFF}}{\tau_{\rm ON} + \tau_{\rm OFF}} \, ,$$

where $f_{\rm ON}$ and $f_{\rm OFF}$ are the fractions of CP-even amplitude calculated from the Dalitz model. Since the events in the ON and OFF regions are topologically equal, the systematic effects due to the resolution function are greatly reduced.

We used untagged data sample to increase sensitivity; on 673 fb^{-1} of Belle data we found 72×10^3 events in the ON region and 62×10^3 events in the OFF region with 97% and 91% signal purity, respectively. The background was

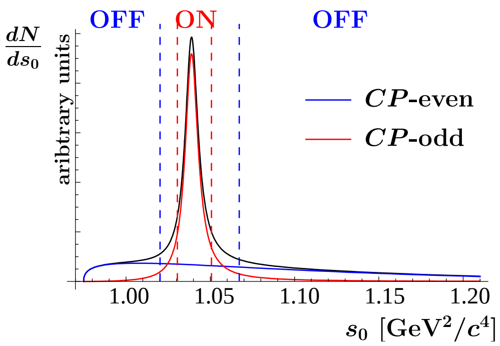

Figure 3: Projection of time-integrated Dalitz distribution to $s_0 \equiv M^2_{KK}$ showing the contributions of CP-even and CP-odd components in the region of ϕ resonance.

estimated from sidebands in (m_{D^0}, m_{K_s}) plane. The fractions $f_{\rm ON}$ and $f_{\rm OFF}$ were determined from the fit to M_{KK} distribution using 8-resonance Dalitz model. The effective lifetimes $\tau_{\rm ON}$ and $\tau_{\rm OFF}$ are evaluated from mean proper decay times of all events in the (m_{D^0}, m_{K_s}) signal region ($\langle t \rangle$) and background events in the (m_{D^0}, m_{K_s}) sideband region ($\langle t \rangle_b$) and known signal fraction (p) as:

$$\tau_R = \frac{\langle t \rangle^R - (1-p^R)\langle t \rangle_b^R}{p^R}, \quad R = \{\mathrm{ON}, \mathrm{OFF}\}.$$

We measured $y_{CP} = (0.11 \pm 0.61(\mathrm{stat.}) \pm 0.52(\mathrm{syst.}))\%$.

Time-dependent Dalitz analysis of $D^0 \to K^0_s \pi^+\pi^-$

A measurement of mixing parameters in the self-conjugate decays $D^0 \to K^0_s\pi^+\pi^-$ was performed using a time-dependent Dalitz plot analysis [5]. The time dependence of the $K^0_s\pi^+\pi^-$ Dalitz plot distribution allows one to measure x and y directly.

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

$$\mathcal{M}(m^2_-, m^2_+, t) = \mathcal{A}(m^2_-, m^2_+)\frac{e_1(t)+e_2(t)}{2} + \frac{q}{p}\overline{\mathcal{A}}(m^2_-, m^2_+)\frac{e_1(t)-e_2(t)}{2}$$

where $\mathcal{A}(\overline{\mathcal{A}})$ is the decay amplitude for $D^0(\overline{D}^0)$ as a function of the invariant masses squared, $m^2_\pm = m(K_s, \pi^\pm)^2$; 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):

$$\mathcal{A}(m^2_-, m^2_+) = \sum_r a_r e^{i\phi_r}\mathcal{A}_r(m^2_-, m^2_+) + a_{NR}e^{i\phi_{NR}}$$

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

The K^0_s was reconstructed in the decay to the $\pi^+\pi^-$ final state; an invariant mass within ± 10 MeV of $m_{K^0_s}$ 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 $M \equiv m_{K^0_s\pi\pi}$ and $Q \equiv m_{K^0_s\pi\pi\pi_s} - m_{K^0_s\pi\pi} - m_\pi$. In the signal region, defined as 3σ intervals in M and Q, 534×10^3 signal events were found, with background fractions of 1% and 4% for the random π_s and combinatorial backgrounds, respectively.

For the events in the signal region, a simultaneous unbinned likelihood fit to the Dalitz plot variables m^2_- and m^2_+, and the decay time t was performed. The free parameters in the fit were x, y, τ_{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. Assuming negligible CP violation, we measured $x = (0.80 \pm 0.29^{+0.09}_{-0.07}{}^{+0.10}_{-0.14})\%$ and $y = (0.33 \pm 0.24^{+0.08}_{-0.12}{}^{+0.06}_{-0.08})\%$; 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 $|q/p| = 0.86^{+0.30}_{-0.29}{}^{+0.06}_{-0.03} \pm 0.08$ and $\phi = (-14^{+16}_{-18}{}^{+5}_{-3}{}^{+2}_{-4})^\circ$.

References

[1] L. M. Zhang *et.al.* (Belle collaboration), Phys. Rev. Lett. **96**, 151801 (2006).

[2] M. Starič *et.al.* (Belle collaboration), Phys. Rev. Lett. **98**, 211803 (2007).

[3] M. Starič *et.al.* (Belle collaboration), Phys. Lett. B **670**, 190 (2008).

[4] A. Zupanc *et.al.* (Belle collaboration), arXiv:0905.4185v1 [hep-ex], submitted to Phys. Rev. D.

[5] L. M. Zhang *et.al.* (Belle collaboration), Phys. Rev. Lett. **99**, 131803 (2007).