Search for $CP$ violation and rare decays in charm sector at Belle

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Using more than 920 fb$^{-1}$ data collected with the Belle detector at the KEKB asymmetric-energy $e^+e^-$ collider, we report the first measurement of the $T$-odd moments in the decay $D^0 \rightarrow K_S^0 \pi^0 \pi^+ \pi^-$. We search for $CP$-violation in decays $D^0 \rightarrow K_S^0 K_S^0$ and $D^+ \rightarrow \pi^+ \pi^0$. All the results are consistent with no $CP$ violation. We also report the result from the first search for $D^0$ decays to invisible final states. No significant signal yield is observed and an upper limit is set on the branching fraction at 90\% confidence level.
1. Search for CP Violation and Measurement of the Branching Fraction in the \(D^0 \rightarrow K_S^0 K_S^0\) Decay [1]

CP violation (CPV) in charm meson decays is predicted to be \(O(10^{-3})\) in Standard Model (SM), and it has not been observed yet [2, 3]. However, in the Single Cabibbo-Suppressed decays of \(D\) mesons, possible interference with New Physics (NP) amplitude could lead to non-zero CPV [4], which could lead to physics beyond the SM.

The time-integrated CP asymmetry \(A_{CP}\) is defined as

\[
A_{CP} = \frac{\Gamma(D \rightarrow f) - \Gamma(\bar{D} \rightarrow \bar{f})}{\Gamma(D \rightarrow f) + \Gamma(\bar{D} \rightarrow \bar{f})},
\]  

where \(\Gamma\) is the partial decay width. \(A_{CP}\) includes the terms due to direct CPV and \(D^0 - \bar{D}^0\) mixing.

The raw asymmetry \(A_{raw}\) is measured with different flavors’ cases:

\[
A_{raw} = \frac{N(D \rightarrow f) - N(\bar{D} \rightarrow \bar{f})}{N(D \rightarrow f) + N(\bar{D} \rightarrow \bar{f})},
\]

where \(N\) is the fitted yield. \(A_{raw}\) consists of \(A_{CP}\) and other terms associated with detection efficiency of final-state particles. By measuring \(A_{raw}\) of another decay \(D \rightarrow f'\) with well-measured \(A_{CP}\), we can obtain \(A_{CP}(D \rightarrow f)\) by the relation \(\Delta A_{raw}(f, f') = \Delta A_{CP}(f, f')\). \(D \rightarrow f'\) can be utilized as the normalization mode for branching fraction measurement as well. We select \(D^0 \rightarrow K_S^0 \pi^0\) as \(D \rightarrow f'\) in this study.

The \(D^\pm\) candidates are reconstructed with an addition \(\pi^{\pm}_{slow}\) to identify \(D^0\)'s flavor and to suppress combinatorial background. The signal yield is extracted by an unbinned extended maximum likelihood fit on \(\Delta M \equiv M_{D^\pm} - M_{f^0}\). The fit is done simultaneously for \(D^+\) and \(D^-\) cases. We obtain \(\frac{\Delta \Gamma(D^0 \rightarrow K^0_S K^0_S)}{\Delta \Gamma(D^0 \rightarrow K^0_S \pi^0)} = (1.101 \pm 0.023)\%\) and \(A_{CP}(D^0 \rightarrow K^0_S K^0_S) = (-0.02 \pm 1.52)\%\), which is consistent with null asymmetry.

2. Search for CP Violation in the decay \(D^+ \rightarrow \pi^+ \pi^0\) at Belle [5]

CPV in charm meson decays is expected to be small in the SM. However, in the world average of \(\Delta A_{CP}(D^0 \rightarrow K^+ K^-, D^0 \rightarrow \pi^+ \pi^-) = (-0.656 \pm 0.154)\%\) [6], we found possible non-zero value in the difference, which could be a hint of NP. In addition, ref.[7] also suggests checking a sum rule related to three isospin related \(D \rightarrow \pi \pi\) modes’ asymmetry:

\[
R = \frac{A_{CP}(D^0 \rightarrow \pi^+ \pi^-)}{1 + \frac{4 \Gamma_{\pi^0}(\frac{\tau_{D^0}}{\tau_{f^0}} + \frac{2 \Gamma_{\pi^0}}{3 \tau_{D^0}})}{1 + \frac{4 \Gamma_{\pi^0}(\frac{\tau_{D^0}}{\tau_{f^0}} + \frac{2 \Gamma_{\pi^0}}{3 \tau_{D^0}})}} + \frac{A_{CP}(D^0 \rightarrow \pi^0 \pi^0)}{1 + \frac{4 \Gamma_{\pi^0}(\frac{\tau_{D^0}}{\tau_{f^0}} + \frac{2 \Gamma_{\pi^0}}{3 \tau_{D^0}})}{1 + \frac{4 \Gamma_{\pi^0}(\frac{\tau_{D^0}}{\tau_{f^0}} + \frac{2 \Gamma_{\pi^0}}{3 \tau_{D^0}})}} + \frac{A_{CP}(D^+ \rightarrow \pi^+ \pi^0)}{1 + \frac{4 \Gamma_{\pi^0}(\frac{\tau_{D^0}}{\tau_{f^0}} + \frac{2 \Gamma_{\pi^0}}{3 \tau_{D^0}})}{1 + \frac{4 \Gamma_{\pi^0}(\frac{\tau_{D^0}}{\tau_{f^0}} + \frac{2 \Gamma_{\pi^0}}{3 \tau_{D^0}})}}},
\]

where \(\tau\) is the lifetime of \(D\) mesons. If \(R\) is consistent 0 while \(A_{CP}(D^+ \rightarrow \pi^+ \pi^0)\) is not, it would be a hint of NP.

In this study, we select \(D^+ \rightarrow K_S^0 \pi^+\) as \(D \rightarrow f'\). Both the \(D^{*\pm} \rightarrow D^{\pm} \pi^0_{slow}\) candidates and the untagged \(D^\pm\) candidates are included in the measurement to increase statistics. Signal yield is extracted by a fit on \(M_{D^{*\pm}}\). We obtain \(A_{CP}(D^+ \rightarrow \pi^+ \pi^0) = (+2.32 \pm 1.24 \pm 0.23)\%\) and \(R = (-2.2 \pm 2.7) \times 10^{-3}\).
3. First measurement of $T$-odd moments in $D^0 \rightarrow K^0_S \pi^0 \pi^+ \pi^-$ [8]

The self-conjugated $D^0 \rightarrow K^0_S \pi^0 \pi^+ \pi^-$ can be used for a precise test of $CPV$, and the large statistics due to large branching fraction of 5.2% [9] can enhance the precision of measurement with $O(10^{-3})$. This decay is sensitive to $CPV$ via the $CPT$ theorem [10].

To measure $T$ violation [11, 12, 13, 14], two asymmetry parameters are defined by using scalar triple products $C_T = p_{K_S} \cdot (p_{\pi^+} \times p_{\pi^-})$ and $T_T = p_{K_S} \cdot (p_{\pi^-} \times p_{\pi^+})$:

$$A_T = \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) + \Gamma(C_T < 0)}, \quad \bar{A}_T = \frac{\Gamma(-C_T > 0) - \Gamma(-C_T < 0)}{\Gamma(-C_T > 0) + \Gamma(-C_T < 0)},$$

(3.1)

for $D^0$ and $\bar{D}^0$. Non-zero value of $A_T$ or $\bar{A}_T$ could be due to the final state effect. To eliminate possible final state effect in $A_T$ and $\bar{A}_T$, we define

$$a_{CP}^{T-\text{odd}} = \frac{1}{2}(A_T - \bar{A}_T).$$

(3.2)

Nonzero $a_{CP}^{T-\text{odd}}$ would indicate a clear $T$ violation.

$D^{\pm} \rightarrow D^0 \pi^\pm_{\text{slow}}$ is also reconstructed in this study. We perform a 2-dimensional fit on $\Delta M$ and $M_{D^0}$ of the four cases ($C_T > 0, C_T < 0, -C_T > 0$, and $-C_T < 0$) simultaneously to obtain the yields of the four cases and the asymmetry parameters. We obtain $A_T = (11.60 \pm 0.19\%$ and $a_{CP}^{T-\text{odd}} = (-0.28 \pm 1.38^{+0.23}_{-0.76}) \times 10^{-3}$. Further measurements in nine exclusive regions of the $K^0_S \pi^0 \pi^+ \pi^-$ phase space with resonance ($K^0_S \omega, K^0_S \eta, K^- \rho^+, K^{*+} \rho^-, K^{*-} \pi^+ \pi^0, K^{*+} \pi^- \pi^0, K^{*+} \pi^+ \pi^-, K^0_S \rho^+ \pi^-$, and the reminder) also show no evidence of $CPV$ in those bins.

4. Search for $D^0$ decays to invisible final states at Belle [15]

Branching fractions of $D$ decay to $v\bar{v}$ is helicity suppressed [16] in SM and is predicted as $1.1 \times 10^{-30}$. Under various types of Dark Matter models [16], branching fraction of $D$ decay to invisible final state can be enhanced to $O(10^{-15})$.

To identify $D^0$ decay with invisible final state and to measure its absolute branching fraction, we utilize the charm tagger method [17, 18, 19, 20] to select an recoil $D^0$ sample by reconstructing the process $e^+e^- \rightarrow \bar{c}c \rightarrow D^{(s)}_{\text{tag}}X_{\text{frag}}D^-_{\text{sig}}$ with $D^-_{\text{sig}} \rightarrow \bar{D}_0^0 \pi^-_{\text{slow}}$, where $D^{(s)}_{\text{tag}}$ is a charm particle as a tag, $X_{\text{frag}}$ is the fragmentation system with a few light unflavored particles, $\pi^-_{\text{slow}}$ is a charged pion from $\bar{D}_0^0_{\text{sig}}$, and $\bar{D}_0^0_{\text{sig}}$ is the recoil $D^0$. By the fit on the $M_{D^0} \equiv M_{\text{miss}}(D^{(s)}_{\text{tag}}X_{\text{frag}}\pi^-_{\text{slow}})$, we obtain 694505$^{+1030}_{-1472}$ inclusive $D^0$ yield with Belle data.

Invisible $D^0$ decays are identified by requiring no remaining final-state particles (e.g. tracks, $\pi^0$, and $K^0_L$) associated with $\bar{D}_0^0_{\text{sig}}$. In addition to $M_{D^0}$, we also use the residual energy in the Electromagnetic Calorimeter ($E_{\text{ECL}}$) to identify signals. A two-dimensional extended unbinned maximum likelihood fit on $M_{D^0}$ and $E_{\text{ECL}}$ is performed, and we obtain a signal yield of $-10.2^{+22.1}_{-20.8}$. Since there is no significant yield observed, we set an upper limit of $8.8 \times 10^{-5}$ for $\mathcal{B}(D^0 \rightarrow \text{invisible})$ at the 90% confidence level.
5. summary

We report the $CPV$ measurement in $D^0 \rightarrow K_S^0 K_S^0$ and $D^+ \rightarrow \pi^+ \pi^0$ decays, first measurement of $T$-odd moments in $D^0 \rightarrow K_S^0 \pi^0 \pi^+ \pi^-$, and the first search for rare decay $D^0$ decays to invisible final states by using more than 920 fb$^{-1}$ data of Belle. All the $CPV$ results show null asymmetry, and we observe no significant yield for the $D^0 \rightarrow$invisible decay and we set an upper limit on the branching fraction at 90% confidence level for it. In Belle II, we expect 40 times of integrated luminosity. The $CPV$ and rare decays measurements of charm mesons can be further improved with higher precision.

References