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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 $D^0 \to K_S^0\pi^0\pi^+\pi^-$. We search for CP-violation in decays $D^0 \to K_S^0 K_S^0$ and $D^+ \to \pi^+\pi^0$. 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.

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1. Search for CP Violation and Measurement of the Branching Fraction in the $D^0 \to K_S^0 K_S^0$ 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

$$A_{CP} = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})}, \tag{1.1}$$

where Γ 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:

$$A_{raw} = \frac{N(D \to f) - N(\bar{D} \to \bar{f})}{N(D \to f) + N(\bar{D} \to \bar{f})}, \tag{1.2}$$

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 $D \to f'$ with well-measured A_{CP}, we can obtain $A_{CP}(D \to f)$ by the relation $\Delta A_{raw}(f, f') = \Delta A_{CP}(f, f')$. $D \to f'$ can be utilized as the normalization mode for branching fraction measurement as well. We select $D^0 \to K_S^0 \pi^0$ as $D \to f'$ 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 $\Delta M \equiv M_{D^{*\pm}} - M_{D^0}$. The fit is done simultaneously for D^{*+} and D^{*-} cases. We obtain $\frac{\mathscr{B}(D^0 \to K_S^0 K_S^0)}{\mathscr{B}(D^0 \to K_S^0 \pi^0)} = (1.101 \pm 0.023)\%$ and $A_{CP}(D^0 \to K_S^0 K_S^0) = (-0.02 \pm 1.52)\%$, which is consistent with null asymmetry.

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

CPV in charm meson decays is expected to be small in the SM. However, in the world average of $\Delta A_{CP}(D^0 \to K^+K^-, D^0 \to \pi^+\pi^-) = (-0.656 \pm 0.154)\%$ [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 $D \to \pi\pi$ modes' asymmetry:

$$R = \frac{A_{CP}(D^0 \to \pi^+\pi^-)}{1 + \frac{\tau_{D^0}}{\mathscr{B}_{+-}}\left(\frac{\mathscr{B}_{00}}{\tau_{D^0}} + \frac{2}{3}\frac{\mathscr{B}_{+0}}{\tau_{D^+}}\right)} + \frac{A_{CP}(D^0 \to \pi^0\pi^0)}{1 + \frac{\tau_{D^0}}{\mathscr{B}_{00}}\left(\frac{\mathscr{B}_{+-}}{\tau_{D^0}} + \frac{2}{3}\frac{\mathscr{B}_{+0}}{\tau_{D^+}}\right)} + \frac{A_{CP}(D^+ \to \pi^+\pi^0)}{1 + \frac{3}{2}\frac{\tau_{D^+}}{\mathscr{B}_{+0}}\left(\frac{\mathscr{B}_{00}}{\tau_{D^0}} + \frac{\mathscr{B}_{+-}}{\tau_{D^0}}\right)}, \tag{2.1}$$

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

In this study, we select $D^+ \to K_S^0 \pi^+$ as $D \to f'$. Both the $D^{*\pm} \to D^{\pm}\pi^0_{slow}$ 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 $A_{CP}(D^+ \to \pi^+\pi^0) = (+2.32 \pm 1.24 \pm 0.23)\%$ and $R = (-2.2 \pm 2.7) \times 10^{-3}$.

3. First measurement of T-odd moments in $D^0 \to K_S^0\pi^0\pi^+\pi^-$ [8]

The self-conjugated $D^0 \to K_S^0\pi^0\pi^+\pi^-$ 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 $C_T = \mathbf{p}_{\mathbf{K_S^0}} \cdot (\mathbf{p}_{\pi^+} \times \mathbf{p}_{\pi^-})$ and $\bar{C}_T = \mathbf{p}_{\mathbf{K_S^0}} \cdot (\mathbf{p}_{\pi^-} \times \mathbf{p}_{\pi^+})$:

$$A_T = \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) + \Gamma(C_T < 0)},\ \bar{A}_T = \frac{\Gamma(-\bar{C}_T > 0) - \Gamma(-\bar{C}_T < 0)}{\Gamma(-\bar{C}_T > 0) + \Gamma(-\bar{C}_T < 0)}, \tag{3.1}$$

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

$$a_{CP}^{T\text{-odd}} = \frac{1}{2}(A_T - \bar{A}_T). \tag{3.2}$$

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

$D^{*\pm} \to D^0\pi_{slow}^{\pm}$ is also reconstructed in this study. We perform a 2-dimensional fit on ΔM and M_{D^0} of the four cases ($C_T > 0, C_T < 0, -\bar{C}_T > 0$, and $-\bar{C}_T < 0$) 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 $K_S^0\pi^0\pi^+\pi^-$ phase space with resonance ($K_S^0\omega$, $K_S^0\eta$, $K^{*-}\rho^+$, $K^{*+}\rho^-$, $K^{*-}\pi^+\pi^0$, $K^{*+}\pi^-\pi^0$, $K^{*+}\pi^+\pi^-$, $K_S^0\rho^+\pi^-$, 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 $\nu\bar{\nu}$ is helicity suppressed [16] in SM and is predicted as 1.1×10^{-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 $e^+e^- \to c\bar{c} \to D_{\text{tag}}^{(*)} X_{\text{frag}} \overline{D}_{\text{sig}}^{*-}$ with $\overline{D}_{\text{sig}}^{*-} \to \overline{D}_{\text{sig}}^{0} \pi_{slow}^-$, where $D_{\text{tag}}^{(*)}$ is a charm particle as a tag, X_{frag} is the fragmentation system with a few light unflavored particles, π_{slow}^- is a charged pion from $\overline{D}_{\text{sig}}^{*-}$, and $\overline{D}_{\text{sig}}^{0}$ is the recoil D^0. By the fit on the $M_{D^0} \equiv M_{\text{miss}}(D_{\text{tag}}^{(*)} X_{\text{frag}} \pi_{slow}^-)$, 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, π^0, and K_L^0) associated with $\overline{D}_{\text{sig}}^{0}$. In addition to M_{D^0}, we also use the residual energy in the Electromagnetic Calorimeter (E_{ECL}) to identify signals. A two-dimensional extended unbinned maximum likelihood fit on M_{D^0} and E_{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 8.8×10^{-5} for $\mathscr{B}(D^0 \to \text{invisible})$ at the 90% confidence level.

5. summary

We report the *CPV* measurement in $D^0 \to K_S^0 K_S^0$ and $D^+ \to \pi^+\pi^0$ decays, first measurement of T-odd moments in $D^0 \to K_S^0\pi^0\pi^+\pi^-$, 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 $D^0 \to$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.

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