CPV in charm decays into neutral kaons

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Direct CP violation

- Direct CP asymmetry established in kaon and bottom decays
- Not yet in charm decays, so its search is a top mission in particle physics
- Usually arises from interference between tree and penguin amplitudes
- Most precise measurement from LHCb

\[
\Delta A_{CP} \equiv A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-) \\
= (-1.0 \pm 0.8 \pm 0.3) \times 10^{-3},
\]
Tree-tree interference

- $D^0 \rightarrow K^+K^-, \pi^+\pi^-$ are singly Cabibbo suppressed modes

$$T_{SCS} \propto V_{cd}^*(s)V_{ud}(s) \quad P \propto V_{ci}^*V_{ui} \exp(i\delta)$$

order $\lambda$ (Wolfenstein parameter) strong phase

- Direct CP asymmetry can also be induced by interference between Cabibbo favored and doubly Cabibbo suppressed tree amplitudes

$$T_{CF} \propto V_{cs}^*V_{ud} \quad T_{DCS} \propto V_{cd}^*V_{us} \exp(i\delta)$$

order unity order $\lambda^2$
Weak phase of DCS/CF

- Standard parametrization of CKM matrix

\[
\begin{bmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{bmatrix}
\begin{bmatrix}
c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta_{13}} & 0 & c_{13}
\end{bmatrix}
\begin{bmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

\[
= \begin{bmatrix}
c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\
-s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\
 s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13}
\end{bmatrix}
\]

\[
\phi \equiv Arg \left[ -V_{cd}^*V_{us}/V_{cs}^*V_{ud} \right]
\]

\[
= (-6.2 \pm 0.4) \times 10^{-4}
\]
Belle data

• Belle measurement with 3.2 sigma from zero

\[ A_{CP}(D^+ \rightarrow \pi^+ K_S^0) = (-3.63 \pm 0.94 \pm 0.67) \times 10^{-3} \]

• Note that Ks is reconstructed via decay into two charged pions

• KL also decays into two pions

• Data mainly due to kaon mixing of order \(10^{-3}\)

• Postulated in literature: deducting kaon mixing, data reveal direct CP asymmetry in charm decays

Lipkin, Xing 1999
D’Ambrosio, Gao 2001
Bianco, Fabbri, Benson, Bigi 2003
Grossman, Nir 2012
Our observation

• This is not correct
• Kaon mixing induces a new CP observable
• More complicated than ordinary mixing-induced CP asymmetry in, say, \( B^0(t) \rightarrow \pi^+\pi^- \): both oscillation and decay occur in mother particle
• The new observable arises from interference between mother decay and daughter mixing
“Strong phase” from oscillation

• Ordinary mixing-induced CP violation

\[ B^0 (\bar{b}d) \rightleftharpoons \bar{B}^0 (b\bar{d}) \]

\[ f_{CP} \]

• \( \exp(i \Delta m t) \) plays the role of “strong phase”

• Feature of CP violation from oscillation: as \( t \to 0 \), it vanishes
Time-dependent CP violation

- The rest is detail
- Consider

\[
A_{CP}(t) \equiv \frac{\Gamma_{\pi\pi}(t) - \overline{\Gamma}_{\pi\pi}(t)}{\Gamma_{\pi\pi}(t) + \overline{\Gamma}_{\pi\pi}(t)}
\]

\[
\Gamma_{\pi\pi}(t) \equiv \Gamma(D \rightarrow fK(t)(\rightarrow \pi^+\pi^-))
\]

\[
\overline{\Gamma}_{\pi\pi}(t) \equiv \Gamma(\overline{D} \rightarrow \overline{f}K(t)(\rightarrow \pi^+\pi^-))
\]

\[
K^0(t) \text{ or } \overline{K}^0(t)
\]
Relevant variables

- Kaon mixing
  \[ |K_{S,L}^0\rangle = p |K^0\rangle ± q |\bar{K}^0\rangle \]
  \[
  q/p = (1 - \epsilon)/(1 + \epsilon) \\
  |\epsilon| = (2.228 ± 0.011) \times 10^{-3} \quad \phi_\epsilon = 43.52 ± 0.05^\circ
  \]
- Indirect CP violation
- Averaged width
  \[ \Gamma = (\Gamma_S + \Gamma_L)/2 \]
- Width difference
  \[ \Delta \Gamma \equiv \Gamma_S - \Gamma_L \]
- Mass difference
  \[ \Delta m \equiv m_L - m_S \]
- Ratio of DCS/CF
  \[
  A(D \rightarrow f K^0)/A(D \rightarrow f \bar{K}^0) = r_f e^{i(\phi + \delta_f)} \\
  r_f \propto |V_{cd}^* V_{us}/V_{cs}^* V_{ud}| \sim \mathcal{O}(10^{-2})
  \]
3 CP observables

- Neglect direct CP asymmetry in $K \rightarrow \pi \pi$

$$A_{CP}(t) \sim \left[ A_{CP}^0(t) + A_{CP}^{dir}(t) + A_{CP}^{int}(t) \right] / D(t)$$

- Known kaon mixing

$$D(t) = e^{-\Gamma_{st} t} (1 - 2r_f \cos \delta_f \cos \phi)$$

$$A_{CP}^0(t) = 2e^{-\Gamma_{st} t} \Re(\epsilon) - 2e^{-\Gamma_{t}} \left[ \Re(\epsilon) \cos(\Delta m t) + \Im(\epsilon) \sin(\Delta m t) \right]$$

- Direct CP asymmetry

$$A_{CP}^{dir}(t) = e^{-\Gamma_{st} t} 2r_f \sin \delta_f \sin \phi$$

- New observable

$$A_{CP}^{int}(t) = -4r_f \cos \phi \sin \delta_f \left[ e^{-\Gamma_{st} t} \Im(\epsilon) \right.$$  
$$- e^{-\Gamma_{t}} \left( \Im(\epsilon) \cos(\Delta m t) - \Re(\epsilon) \sin(\Delta m t) \right) \left. \right]$$
Global fits

- Adopt factorization-assisted topological-amplitude approach

- DCS/CF parameters for $D^+ \rightarrow \pi^+ K_S^0$ and $D_s^+ \rightarrow K^+ K_S^0$

  $r_{\pi^+} = -0.073 \pm 0.004$,  \hspace{1cm} \delta_{\pi^+} = -1.39 \pm 0.05,$

  $r_{K^+} = -0.055 \pm 0.002$,  \hspace{1cm} \delta_{K^+} = +1.45 \pm 0.05$

- Direct CP asymmetry at $t=0$

  \begin{align*}
  A_{CP}^{\text{dir}}(D^+ \rightarrow \pi^+ K_S^0) & = (-8.6 \pm 0.4) \times 10^{-5} \\
  A_{CP}^{\text{dir}}(D_s^+ \rightarrow K^+ K_S^0) & = (6.6 \pm 0.3) \times 10^{-5}. 
  \end{align*}
Numerical results

• Direct CP asymmetry always negligible

• New observable becomes comparable to kaon mixing as $t \sim$ few times of K short lifetime
Experimental verification

• To verify the new CP violation effect, measure

$$\Delta A^\pi_{CP} \equiv A^{D^+ \rightarrow \pi^+ K_S^0}_{CP}(t_1, t_2) - A^{D_s^+ \rightarrow K^+ K_S^0}_{CP}(t_1, t_2)$$

$$\approx A^{int, D^+ \rightarrow \pi^+ K_S^0}_{CP}(t_1, t_2) - A^{int, D_s^+ \rightarrow K^+ K_S^0}_{CP}(t_1, t_2)$$

where time-integrated CP asymmetry

$$A_{CP}(t_1, t_2) = \frac{\int_{t_1}^{t_2} \left[ A^{K_S^0}_{CP}(t) + A^{dir}_{CP}(t) + A^{int}_{CP}(t) \right] dt}{\int_{t_1}^{t_2} D(t) dt}$$

• Kaon mixing cancels in the difference, and direct CP asymmetry is negligible
Theoretical prediction

\[ \Delta A_{CP}^{\pi^+, K^+} \times 10^{-3} \]
Conclusion

• New effect, from interference between mother decay and daughter mixing, can be measured at Belle II and LHCb upgrade with precision of $\mathcal{O}(10^{-4})$

• If verified, need to be subtracted in order to extract direct CP asymmetry in charm decays

• Then direct CP asymmetry from DCS and CF interference, both being tree and better controlled by branching-ratio data, can be used to test new physics
Direct CPA in Belle data

• Recall Belle data

\[ A_{CP}(D^+ \rightarrow \pi^+ K^0_s) = (-3.63 \pm 0.94 \pm 0.67) \times 10^{-3} \]

• Consider the integrated CP asymmetry in the limit

\[ A_{CP}(t_1 \ll \tau_S \ll t_2 \ll \tau_L) \approx \frac{-2\Re(\epsilon) + 2r_f \sin \phi \sin \delta_f - 4\Im(\epsilon)r_f \cos \phi \sin \delta_f}{1 - 2r_f \cos \phi \cos \delta_f} \]

• Extract direct CP asymmetry from Belle data

\[ (-0.06 \pm 1.15) \times 10^{-3} \]
Back-up slides
Cabbibo-Kobayashi-Maskawa Matrix

\[
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
= 
\begin{pmatrix}
1 - \frac{1}{2} \lambda^2 & \lambda & A\lambda^3 (\rho - i\eta) \\
-\lambda & 1 - \frac{1}{2} \lambda^2 & A\lambda^2 \\
A\lambda^3 (1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix} + O(\lambda^4)
\]

(Wolfenstein parametrization)

\[
\begin{pmatrix}
0.97 & 0.23 & 0.004 \\
-0.23 & 0.97 & 0.04 \\
0.004 & -0.04 & 1
\end{pmatrix}
\]

(magnitudes only)

Weak phase, $\varphi_P$
U-spin symmetry

- Ratio of DCS/CF

\[ D^+ \rightarrow \pi^+ K_S^0 \]

\[ D_s^+ \rightarrow K^+ K_S^0 \]

- Reason why strong phase opposite in sign