CP violation in charm

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Murphy’s law:

Modern charm physics experiments acquire ample statistics; many decay rates are quite large.

THUS:

It is very difficult to provide model-independent theoretical description of charmed quark systems.

Now, this does not apply to CP-violation in charm: both measurements and predictions are hard...
In any quantum field theory CP-symmetry can be broken

1. Explicitly through dimension-4 operators ("hard")
   
   Example: Standard Model (CKM): \[ \bar{\psi}_i \psi_k \overset{CP}{\to} \bar{\psi}_k \psi_i, \quad \varphi \overset{CP}{\to} \varphi \]
   
   \[ \mathcal{L}_{Yuk} = \zeta_{ik} \bar{\psi}_i \psi_k \varphi + \text{H.c.} \overset{CP}{\not=} \mathcal{L}_{Yuk} \]

2. Explicitly through dimension <4 operators ("soft")

   Example: SUSY

3. Spontaneously (CP is a symmetry of the Lagrangian, but not of the ground state)

   Example: multi-Higgs models, left-right models

These mechanisms can be probed in charm transitions
Possible sources of CP violation in charm transitions:

- CPV in $\Delta c = 1$ decay amplitudes (“direct” CPV)
  \[ A(D \to f) \equiv A_f = |A_1| e^{i\delta_1} e^{i\phi_1} + |A_2| e^{i\delta_2} e^{i\phi_2}, \quad \Delta \delta \neq 0, \Delta \phi \neq 0 \]

- CPV in $D^0 - \bar{D}^0$ mixing matrix ($\Delta c = 2$)
  \[ R_m^2 = \frac{|p|^2}{q^2} = \frac{2M_{12} - i\Gamma_{12}}{2M_{12}^* - i\Gamma_{12}^*} \neq 1 \]

- CPV in the interference of decays with and without mixing
  \[ \lambda_f = \frac{q}{p} \frac{\overline{A}_f}{A_f} = R_m e^{i(\phi + \delta)} \frac{|\overline{A}_f|}{A_f} \]

One can separate various sources of CPV by customizing observables.
Comment

➢ Generic expectation is that CP-violating observables in the SM are small

\[ \Delta c = 1 \text{ amplitudes} \]

\[ V_{ud} V_{cd}^* + V_{us} V_{cs}^* + V_{ub} V_{cb}^* = 0 \]

\[ \sim \lambda \sim \lambda \sim \lambda^5 \]

Penguin amplitude

➢ The Unitarity Triangle for charm:

\[ \text{With } b\text{-quark contribution neglected: only 2 generations contribute} \]

\[ \Rightarrow \text{real } 2\times2 \text{ Cabibbo matrix} \]

Any CP-violating signal in the SM will be small, at most \( O(V_{ub} V_{cb}^* / V_{us} V_{cs}^*) \sim 10^{-3} \)

Thus, \( O(1\%) \) CP-violating signal can provide a "smoking gun" signature of New Physics
There exists a variety of CP-violating observables

1. "Static" observables, such as electric dipole moment

2. "Dynamical" observables:
   a. Transitions that are forbidden in the absence of CP-violation
      \[ CP[\text{initial state}] \neq CP[\text{final state}] \]
   b. Mismatch of transition probabilities of CP-conjugated processes
      \[ \Gamma(D \rightarrow f) \neq \Gamma(\bar{D} \rightarrow \bar{f}) \]
   c. Various asymmetries in decay distributions, etc.

Depending on the initial and final states, these observables can be affected by all three sources of CP-violation
a. Transitions forbidden w/out CP-violation

Recall that CP of the states in $D^0 \bar{D}^0 \rightarrow (F_1)(F_2)$ are anti-correlated at $\psi(3770)$:

- a simple signal of CP violation: $\psi(3770) \rightarrow D^0 \bar{D}^0 \rightarrow (CP\pm)(CP\pm)$

\[
\begin{align*}
CP[f_1] &= CP[f_2] \\
\{ \begin{array}{c}
\bar{f}_1 \\
\bar{f}_2 \\
f_2 \\
f_1 \\
\end{array} \} & \quad CP \text{ eigenstate } f_2 \\
\{ \begin{array}{c}
\bar{f}_1 \\
f_1 \\
\end{array} \} & \quad CP \text{ eigenstate } f_1
\end{align*}
\]

\[
\left| D^0 \bar{D}^0 \right>_L = \frac{1}{\sqrt{2}} \left[ \left| D^0(k_1) \bar{D}^0(k_2) \right> + (-1)^L \left| D^0(k_2) \bar{D}^0(k_1) \right> \right]
\]

\[
\Gamma_{F_1F_2} = \frac{\Gamma_{F_1} \Gamma_{F_2}}{2 R_m} \left[ \left( 2 + x^2 + y^2 \right) \left| \lambda_{F_1} - \lambda_{F_2} \right|^2 + \left( x^2 + y^2 \right) \left| 1 - \lambda_{F_1} \lambda_{F_2} \right|^2 \right]
\]

- CP-violation in the rate $\rightarrow$ of the second order in CP-violating parameters.
- Cleanest measurement of CP-violation!
What if \( f_1 \) or \( f_2 \) is not a CP-eigenstate

- If CP violation is neglected: mass eigenstates = CP eigenstates
- CP eigenstates do NOT evolve with time, so can be used for “tagging”

\[
\begin{align*}
&\text{CP Eigenstate (-)} \\
&\begin{cases}
K_S \\
\pi^0
\end{cases}
\end{align*}
\]

\[
\begin{align*}
&\frac{1}{\sqrt{2}} \left[ D^0(k_1) \bar{D}^0(k_2) \right] + (-1)^L \left[ D^0(k_2) \bar{D}^0(k_1) \right]
\end{align*}
\]

- \( \tau \)-charm factories have good CP-tagging capabilities
  - CP anti-correlated \( \psi(3770) \): CP(tag) \((-1)^L = [\text{CP}(K_S) \text{CP}(\pi^0)] (-1) = +1 \)
  - CP correlated \( \psi(4140) \)

Can measure \((y \cos \phi)\):

\[
B^l_{\pm} = \frac{\Gamma(D_{CP\pm} \rightarrow X l \nu)}{\Gamma_{tot}}
\]

\[
y \cos \phi = \frac{1}{4} \left( \frac{B^l_+}{B^-} - \frac{B^-}{B^+_+} \right)
\]

D. Atwood, A.A.P., hep-ph/0207165
D. Asner, W. Sun, hep-ph/0507238
b. Mismatch of transition probabilities

- At least two components of the transition amplitude are required

Look at charged D's:

\[ A(D^+ \rightarrow f) \equiv A_f = |A_1|e^{i\delta_1}e^{i\phi} + |A_2|e^{i\delta_2}e^{i\phi_2} \]

Then, a charge asymmetry will provide a CP-violating observable

\[
a_f = \frac{\Gamma(D^+ \rightarrow f) - \Gamma(D^- \rightarrow f)}{\Gamma(D^+ \rightarrow f) + \Gamma(D^- \rightarrow f)} = \frac{2 \text{Im} A_1 A_2^* \sin(\delta_1 - \delta_2)}{|A_1|^2 + |A_2|^2 + 2 \text{Re} A_1 A_2^* \cos(\delta_1 - \delta_2)}
\]

...or, introducing \( r_f = |A_2/A_1| \):

\[ a_f = 2r_f \sin \phi \sin \delta \]

- Same formalism applies if one of the amplitudes is generated by New Physics

need \( r_f \sim 1\% \) for \( O(1\%) \) charge asymmetry
b. Mismatch of transition probabilities - II

- This can be generalized for neutral D-mesons too:

\[
 a_f = \frac{\Gamma(D \to f) - \Gamma(D \to \bar{f})}{\Gamma(D \to f) + \Gamma(D \to \bar{f})} \quad \text{and} \quad a_{\bar{f}} = \frac{\Gamma(D \to \bar{f}) - \Gamma(D \to f)}{\Gamma(D \to f) + \Gamma(D \to \bar{f})}
\]

- Each of those asymmetries can be expanded as

\[
a_f = a_f^d + a_f^m + a_f^i
\]

- direct mixing interference

\[
a_f^d = 2r_f \sin \phi_f \sin \delta_f
\]

\[
a_f^m = -R_f \frac{y_f'}{2} (R_m - R_m^{-1}) \cos \phi
\]

\[
a_f^i = R_f \frac{x_f'}{2} (R_m + R_m^{-1}) \sin \phi
\]

1. similar formulas available for \( \bar{f} \)
2. for CP-eigenstates: \( f = \bar{f} \) and \( y_f' \to y \)

Those observables are of the first order in CPV parameters, but require tagging.
What to expect?

- **Standard Model asymmetries (in $10^{-3}$):**

<table>
<thead>
<tr>
<th>Final state</th>
<th>$\pi^+\eta$</th>
<th>$\pi^+\eta'$</th>
<th>$K^+\overline{K}^0$</th>
<th>$\pi^+\rho^0$</th>
<th>$\pi^0\rho^+$</th>
<th>$K^*+\overline{K}^0$</th>
<th>$K^<em>\overline{K}^</em>$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_f, \cos\delta &gt; 0$</td>
<td>-1.5±0.4</td>
<td>0.04±0.01</td>
<td>1.0±0.3</td>
<td>-2.3±0.6</td>
<td>2.9±0.8</td>
<td>-0.9±0.3</td>
<td>2.8±0.8</td>
</tr>
<tr>
<td>$a_f, \cos\delta &lt; 0$</td>
<td>-0.7±0.4</td>
<td>0.02±0.01</td>
<td>0.5±0.3</td>
<td>-1.2±0.6</td>
<td>1.5±0.8</td>
<td>-0.5±0.3</td>
<td>1.4±0.7</td>
</tr>
</tbody>
</table>


- **New Physics (in new tree-level interaction and new loop effects):**

<table>
<thead>
<tr>
<th>Model</th>
<th>$r_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extra quarks in vector-like rep</td>
<td>&lt; $10^{-3}$</td>
</tr>
<tr>
<td>RPV SUSY</td>
<td>&lt; $1.5\times10^{-4}$</td>
</tr>
<tr>
<td>Two-Higgs doublet</td>
<td>&lt; $4\times10^{-4}$</td>
</tr>
</tbody>
</table>

HFAG provides the following averages from BaBar, Belle, CDF, E687, E791, FOCUS, CLEO collaborations

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>CP asymmetry</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 \to K^+ K^-$</td>
<td>+ 0.0136 ± 0.012</td>
</tr>
<tr>
<td>$D^0 \to K_S^0 K_S^0$</td>
<td>− 0.23 ± 0.19</td>
</tr>
<tr>
<td>$D^0 \to \pi^+ \pi^-$</td>
<td>+ 0.0127 ± 0.0125</td>
</tr>
<tr>
<td>$D^0 \to \pi^0 \pi^0$</td>
<td>+ 0.001 ± 0.048</td>
</tr>
<tr>
<td>$D^0 \to \pi^+ \pi^- \pi^0$</td>
<td>+ 0.01 ± 0.09</td>
</tr>
<tr>
<td>$D^0 \to K_S^0 \pi^0$</td>
<td>+ 0.001 ± 0.013</td>
</tr>
<tr>
<td>$D^0 \to K^- \pi^+ \pi^0$</td>
<td>− 0.031 ± 0.086</td>
</tr>
<tr>
<td>$D^0 \to K^- \pi^- \pi^0$</td>
<td>− 0.001 ± 0.052</td>
</tr>
<tr>
<td>$D^0 \to K_S^0 \pi^+ \pi^-$</td>
<td>− 0.009 ± 0.042</td>
</tr>
<tr>
<td>$D^0 \to K^- \pi^- \pi^+ \pi^-$</td>
<td>− 0.018 ± 0.044</td>
</tr>
<tr>
<td>$D^0 \to K^+ K^- \pi^+ \pi^-$</td>
<td>− 0.082 ± 0.073</td>
</tr>
</tbody>
</table>

Most measurements are at the percent sensitivity
Time-dependent observables

Time dependent $D^0(t) \rightarrow K^+K^-$ (lifetime difference analysis):
separate datasets for $D^0$ and $\bar{D}^0$

\[
\Delta Y_{KK} = \frac{\Gamma'(D^0 \rightarrow K^+K^-) - \Gamma'(\bar{D}^0 \rightarrow K^+K^-)}{\Gamma'(D^0 \rightarrow K^+K^-) + \Gamma'(\bar{D}^0 \rightarrow K^+K^-)} = \frac{A_m}{2} y \cos \phi - x \sin \phi
\]

$\Delta Y_{KK} = a_{KK}^m + a_{KK}^i$ universal for all final states

This analysis requires

1. time-dependent studies
2. initial flavor tagging ("the $D^*$ trick")

BaBar [2003]: $\Delta Y=(-0.8 \pm 0.6 \pm 0.2) \times 10^{-2}$
Belle [2003]: $\Delta Y=(+0.20 \pm 0.63 \pm 0.30) \times 10^{-2}$

World average: $\Delta Y=(-0.35 \pm 0.47) \times 10^{-2}$
Untagged observables

Look for CPV signals that are

1. first order in CPV
2. do not require flavor tagging

Consider the final states that can be reached by both \( \bar{D}^0 \) and \( D^0 \), but are not CP eigenstates (\( \pi \rho, K K^*, K \pi, K \rho, \ldots \))

\[
A_{CP}^U(f, t) = \frac{\Sigma_f - \Sigma_{\bar{f}}}{\Sigma_f + \Sigma_{\bar{f}}}
\]

where

\[
\Sigma_f = \Gamma(D^0 \to f)[t] + \Gamma(\bar{D}^0 \to f)[t]
\]

A.A.P., PRD69, 111901(R), 2004
hep-ph/0403030
CP violation: untagged asymmetries

Expect time-dependent asymmetry...

\[ A_{CP}^{U}(f,t) = \frac{1}{D(t)} e^{-\Gamma t} \left[ A + B (\Gamma t) + C (\Gamma t)^2 \right] \]

... and time-integrated asymmetry

\[ A_{CP}^{U}(f,t) = \frac{1}{D} [A + B + 2C] \]

... whose coefficients are computed to be

\[
A = \left| A_f \right|^2 \left[ \left( 1 - \left| \overline{A_f} \right|^2 / \left| A_f \right|^2 \right) + R \left( 1 - \left| A_f \right|^2 / \left| \overline{A_f} \right|^2 \right) \right],
\]

\[
B = -2y \sqrt{R} \sin \phi \sin \delta \left( \left| \overline{A_f} \right|^2 + \left| A_f \right|^2 \right) - \cos \phi \cos \delta \left( \left| \overline{A_f} \right|^2 - \left| A_f \right|^2 \right),
\]

\[
C = \frac{x^2}{2} A.
\]

This is true for any final state \( f \)
CP violation: untagged asymmetries ($K^+\pi^-$)

For a particular final state $K\pi$, the time-integrated asymmetry is simple

\[ A_{CP}^{U}(K^+\pi^-) = -y \sin \delta \sin \phi \sqrt{R} \]

This asymmetry is

1. non-zero due to large SU(3) breaking
2. contains no model-dependent hadronic parameters ($R$ and $\delta$ are experimental observables)
3. could be as large as 0.04% for NP

Note: larger by $O(100)$ for SCS decays ($\pi\rho$, ...) where $R \sim 1$
Other observables can be constructed for baryons, e.g.

\[ A(\Lambda_c \rightarrow N\pi) = \bar{u}_N(p,s)[A_S + A_P\gamma_5]u_{\Lambda_c}(p_{\Lambda_c},s_{\Lambda_c}) \]

These amplitudes can be related to “asymmetry parameter”

\[ \alpha_{\Lambda_c} = \frac{2 \text{Re}(A_S^*A_P)}{|A_S|^2 + |A_P|^2} \]

... which can be extracted from

\[ \frac{dW}{d\cos\theta} = \frac{1}{2}(1 + P\alpha_{\Lambda_c}\cos\theta) \]

If CP is conserved \( \alpha_{\Lambda_c}^{CP} \Rightarrow -\alpha_{\Lambda_c} \), thus CP-violating observable is

\[ A_f = \frac{\alpha_{\Lambda_c} + \bar{\alpha}_{\Lambda_c}}{\alpha_{\Lambda_c} - \bar{\alpha}_{\Lambda_c}} \]

FOCUS[2006]: \( A_{\Lambda\pi} = -0.07\pm0.19\pm0.24 \)
Conclusions

- Charm provides great opportunities for New Physics studies
  - large available statistics
  - small Standard Model background
- Different observables should be used to disentangle CP-violating contributions to $\Delta c=1$ and $\Delta c=2$ amplitudes
  - time-dependent and time-independent charge asymmetries
  - CP-tagged measurements
- Observation of CP-violation in the current round of experiments provide “smoking gun” signals for New Physics
  - new observables should be considered
    - untagged CP-asymmetries
    - triple-product correlators in $D \to VV$ decays
    - CP-asymmetries in baryon decays
Additional slides
“Static” observables for CP-violation

I. Intrinsic particle properties

✓ electric dipole moments:

\[ \mathbf{d} = \int d^3 x \, \mathbf{x} \rho(\mathbf{x}) \]

should be (anti-)alligned with spin \( \mathbf{s} \)!

\[ \mathbf{d} \xrightarrow{T} \mathbf{d} \quad || \quad \mathbf{s} \xrightarrow{T} -\mathbf{s} \]

however

\[ \mathbf{d} \xrightarrow{P} -\mathbf{d} \quad || \quad \mathbf{s} \xrightarrow{P} \mathbf{s} \]

thus, if \( \mathbf{d} \neq 0 \) \( \Rightarrow T \) or \( CP \) is broken

<table>
<thead>
<tr>
<th>Particle</th>
<th>Exp Limit, e cm</th>
<th>Theory (SM), e cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>neutron</td>
<td>(</td>
<td>d_n</td>
</tr>
<tr>
<td>electron</td>
<td>(</td>
<td>d_e</td>
</tr>
<tr>
<td>muon</td>
<td>(</td>
<td>d_\mu</td>
</tr>
</tbody>
</table>

Low energy strong interaction effects might complicate predictions!