CP Violation in the $B$ Meson System

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Outline

• Refresher (hadrons, \( C, P, \) and \( T \))

• Historical background

• Why is it interesting to study \( CP \) violation?

• How \( CPV \) arises in the Standard Model
  - \( B \) meson decays and \( B \)-Factories
Review of Basic Principles
Particle Zoo 101

- For each fundamental particle $x$ there is an antiparticle $\bar{x}$

- Observed particles are the leptons and bound states of quarks (hadrons) two types:

<table>
<thead>
<tr>
<th>Mesons (bosons) $q\bar{q}'$</th>
<th>Baryons (fermions) $q_1q_2q_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u\bar{d} = \pi^+$</td>
<td>$uud = p$</td>
</tr>
<tr>
<td>$u\bar{s} = K^+$</td>
<td>$udd = n$</td>
</tr>
<tr>
<td>$d\bar{s} = K^0$</td>
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</tbody>
</table>

- **Strong force** keeps quarks bound into hadrons
- **Weak force** responsible for radioactive decay $\Rightarrow$ lepton and quark flavor changes
Discrete Operations

• The field equations (Lagrangians) for particle interactions are symmetric under certain discrete operations or transformations.

• Invariance of these equations under such transformations imply existence of conserved, multiplicative quantum numbers.

• There are 3 particularly important such operations in particle physics...
**C: Charge Conjugation**

Charged particle wavefunctions not eigenstates

\[ C |e^-\rangle = |e^+\rangle \neq \pm |e^-\rangle \]

Many neutral particles are (eigenvalue \(\pm 1\))

\[ C |\gamma\rangle = -|\gamma\rangle \quad C |\pi^0\rangle = +|\pi^0\rangle \]
**P: Parity**

Reflects a system through the origin

- \(x \rightarrow -x\) and \(p \rightarrow -p\)
- but \(L \rightarrow L\)

Particles have intrinsic parity:

\[ P |\gamma\rangle = -|\gamma\rangle \quad P |\pi^0\rangle = -|\pi^0\rangle \]

**Fermions:** opposite parity for particle and antiparticle

**Bosons:** same parity for particle and antiparticle
$T$: Time Reversal

Reverses direction of time

$- t \rightarrow -t$

$- p \rightarrow -p$
The CPT Theorem

- These 3 operations are connected through invariance of combined CPT for all forces

- CPT Theorem: all field theories are invariant under this combo of operations (any order)
  - Consequences:
    - particles and antiparticles have same mass and lifetime
    - particles obey spin statistics (Fermi or Bose)
Conservation of $C$, $P$, and $T$?

Strong, electromagnetic and gravitational interactions are observed to be invariant under $C$, $P$, and $T$, separately.

Weak Interaction...

- It conserves neither $C$ nor $P$.
- First postulated by Lee and Yang in 1956 and verified in studies of $\beta$ decay of Cobalt.
- Later observed in many other systems (neutrinos, etc.).
Violation of $C$ and $P$ in Weak Decays

Neutrino system:

$$\nu_L \xrightarrow{C} \bar{\nu}_L$$
$$\nu_L \xrightarrow{P} \nu_R$$

Neither of these states are observed in nature

Example ⇒ Pion decay:

$$\Gamma(\pi^+ \rightarrow \mu^+ \nu_L) \neq \Gamma(\pi^- \rightarrow \mu^- \bar{\nu}_L) = 0 \quad C\text{ violation}$$
$$\Gamma(\pi^+ \rightarrow \mu^+ \nu_L) \neq \Gamma(\pi^+ \rightarrow \mu^+ \nu_R) = 0 \quad P\text{ violation}$$
For a long time it was thought that CP was conserved in weak interactions:

\[ \Gamma(\pi^+ \to \mu^+ \nu_L) = \Gamma(\pi^- \to \mu^- \bar{\nu}_R) \]

\[ \Rightarrow CP \text{ invariance} \]

But in 1964, an expt by Christenson, Cronin, Fitch and Turlay first demonstrated CP violation in the weak decays of \( K^0 \) mesons.
CPV in Kaon Decays

• Two distinct neutral kaon states had been observed:
  \( K_1^0 \rightarrow \) short lifetime, \( CP \) even (eigenvalue +1)
  \( K_2^0 \rightarrow \) long lifetime, \( CP \) odd (eigenvalue -1)

\[
\begin{align*}
\tau (K_1^0 \rightarrow 2\pi) & = 0.9 \times 10^{-10} \text{ sec} \\
\tau (K_2^0 \rightarrow 3\pi) & = 0.5 \times 10^{-7} \text{ sec}
\end{align*}
\]

• The 1964 expt discovered the longer-lived kaon decaying, very rarely (~10^{-3}) to the \( 2\pi, \ CP = +1 \) state

\[
\begin{align*}
|K_L^0\rangle & = |K_2\rangle + \varepsilon |K_1\rangle \\
|K_S^0\rangle & = |K_1\rangle - \varepsilon |K_2\rangle
\end{align*}
\]

| \( \varepsilon \) | \( \approx 2 \times 10^{-3} \) |
Why Such Interest in $CP$ Violation?
Interest in $CP$ Violation

• What is it about the weak interaction that generates $CP$ violation?
  - It is naturally present in the Standard Model of particle physics

• Can we observe it in decays of other particles besides the kaon?
  - Compare measurements with predictions of the Standard Model

• Can we observe the effects of New Physics?
  - Super Symmetry, String Theory $\rightarrow$ sources of more $CPV$
  - Amount of $CPV$ from SM alone does not explain large matter-antimatter asymmetry of present universe
CP Violation in the Standard Model: 
B Meson Decays

\[ B^0 = \bar{b}d \]

\[ \bar{B}^0 = b\bar{d} \]
CPV in the Decays of B Mesons

• As we shall see, CP violation expected to be relatively large (hopefully experimentally observable!) in the decays of B mesons to certain final states.

• “B-Factories” built in US (BaBar) and Japan (Belle) to produce hundreds of millions of B mesons, with goal of looking for CP violation ⇒ differences in B and \( \bar{B} \) decay rates
  ▪ Colliders of e\(^+\) and e\(^-\) beams → production of \( B\bar{B} \) pairs
  ▪ Began running in 1999 and plan to continue until ~2009

• Looking for CP asymmetries...
CP Asymmetries

- Example: Look for CPV in the $B$ meson decay to final state $X$ (system of final state particles)

$$A_{CP} = \frac{\Gamma(\overline{B} \rightarrow \overline{X}) - \Gamma(B \rightarrow X)}{\Gamma(\overline{B} \rightarrow \overline{X}) + \Gamma(B \rightarrow X)}$$

$$\Gamma(B \rightarrow X) \propto |A_X|^2$$

$$\Gamma(\overline{B} \rightarrow \overline{X}) \propto |\overline{A}_X|^2$$

- $\Gamma(B \rightarrow X)$ is the decay rate for $B$ to decay to $X$
- $A_{B \rightarrow X}$ is the “transition amplitude” for this decay (complex #)

- $A_{CP} \neq 0$ is violation of CP conservation
Quark “generation” can change in weak decays (quark mixing):

\[ b \rightarrow c \quad \text{and} \quad b \rightarrow u \]

Not so for leptons:

\[ e^- \rightarrow \nu_e \quad \text{and} \quad e^- \rightarrow \nu_\mu \]
The Weak Couplings of Quarks

- The coupling strength at the vertex is given by
  - $g$ is a *universal* weak coupling
  - $gV_{ij}$ depends on the initial and final state quark
  - For leptons, only $g$ (?)

- The $V_{ij}$ can be written as a matrix (CKM matrix)

- $V_{ij} \Rightarrow V_{ij}^*$ For antiquarks

The transition amplitude, $A$, is proportional to the product of the couplings for each vertex in the given weak decay
Properties of the CKM Matrix

- The CKM matrix is a 3x3 complex, unitary matrix \((V^+V = 1)\)
- This means 4 independent parameters describe it:
  - 3 real numbers
  - 1 complex phase → possibility of CP violation

\[
V_{CKM} = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\]

\[
\begin{pmatrix}
\sqrt{V_{td}}e^{-i\beta} \\
\sqrt{V_{ub}}e^{-i\gamma}
\end{pmatrix}
\]

\[
= \begin{pmatrix}
1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix} + O(\lambda^4)
\]

All elements other than \(V_{td}\) and \(V_{ub}\) are real.
**CPV in B Decays: Example**

- Example: $B^0 \rightarrow K^+ \pi^-$ and $\overline{B}^0 \rightarrow K^- \pi^+$

\[
A_{K^+\pi^-} = |A_{K^+\pi^-}| e^{-i\gamma} e^{i\delta}
\]

\[
\overline{A}_{K^-\pi^+} = |\overline{A}_{K^-\pi^+}| e^{+i\gamma} e^{i\delta}
\]

\[
A_{CP} = 0 \text{ since } |\overline{A}_{K^-\pi^+}|^2 = |A_{K^+\pi^-}|^2
\]

\[\gamma \text{ is the phase from } V_{ub}\]

\[\delta \text{ is any phase from "strong interactions"}\]
**CPV in B Decays: Example**

- But what if a second diagram exists...?

\[
A_{K^+\pi^-}^T = |A_{K^+\pi^-}^T| e^{i(-\gamma + \delta_T)}
\]

\[
A_{K^+\pi^-}^P = |A_{K^+\pi^-}^P| e^{i\delta_P}
\]

Tree

Penguin

\[
A_{K^+\pi^-} = A_{K^+\pi^-}^T + A_{K^+\pi^-}^P = |A_{K^+\pi^-}^T| e^{i(-\gamma + \delta_T)} + |A_{K^+\pi^-}^P| e^{i\delta_P}
\]

\[
\overline{A}_{K^-\pi^+} = \overline{A}_{K^-\pi^+}^T + \overline{A}_{K^-\pi^+}^P = |A_{K^+\pi^-}^T| e^{i(\gamma + \delta_T)} + |A_{K^+\pi^-}^P| e^{i\delta_P}
\]
**CPV in B Decays: Example**

- Now a non-zero *CP* asymmetry can be possible in SM!

\[
A_{\text{CP}} = \frac{\Gamma(B^0 \rightarrow K^+\pi^-) - \Gamma(B^0 \rightarrow K^-\pi^+)}{\Gamma(B^0 \rightarrow K^+\pi^-) + \Gamma(B^0 \rightarrow K^-\pi^+)}
\]

\[
\equiv \frac{|A_{K^+\pi^-}|^2 - |A_{K^-\pi^+}|^2}{|A_{K^+\pi^-}|^2 + |A_{K^-\pi^+}|^2}
\]

\[
= \frac{2|A_T||A_P| \sin \gamma \sin (\delta_T - \delta_P)}{|A_T|^2 + |A_P|^2 + 2|A_T||A_P| \cos \gamma \cos (\delta_T - \delta_P)}
\]

\(\neq 0\) if:

\[
\gamma \neq 0, \pi/2 \\
\delta_T - \delta_P \neq 0, \pi/2
\]
**CPV in B Decays: Example**

- This *CP* asymmetry has just been observed for first time at the *BaBar* experiment!

In sample of ~550 million *B* mesons:

1606±51 \( B^0 \rightarrow K^+ \pi^- \)

decays observed

\[ A_{CP} = -0.133\pm0.030(\text{stat})\pm0.009(\text{syst}) \]
Very interesting and important discovery of *direct CP* violation in *B* meson decays

- But real goal is to try and make a measurement of the Standard Model parameters $\beta$ and $\gamma$

  Not easy because we need theoretical predictions for values of $|A_T|$, $|A_\rho|$ and $\delta_T - \delta_P$

- A “cleaner” way involves measurements of *indirect CP* violation ⇒ see talk by Morii
Summary

• Study of $CP$ violation in Weak decays of particles at forefront of particle physics research:
  - Crucial ingredient in cosmology $\rightarrow$ need to explain how the universe can exist as we observe it today!
  - Arises in the Standard Model (SM) via the single imaginary quantity in the quark-mixing (CKM) matrix, and nowhere else.
  - Until recently (2000), no reliable comparison of experimental measurements and SM predictions $\rightarrow$ effects had been predicted to be largest in decays of $B$ mesons

Advent of $B$-Factories in 1999 to study this phenomenon $\Rightarrow$ Very successful so far! $CP$ asymmetries being observed

Do expt. measurements agree with SM...or New Physics?