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 $\overline{x}$

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

Mesons (bosons) $q\overline{q}'$			Baryons (fermions) $q_1q_2q_3$	
$u\overline{d} = \pi^+$	$u\overline{s} = K^+$	$d\overline{s} = K^0$	$uud = p$	$udd = n$

- 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

Particle ⟶ Anti-particle

Charged particle wavefunctions not eigenstates

$$C\,|e^-\rangle = |e^+\rangle \;\neq\; \pm|e^-\rangle$$

Many neutral particles <u>are</u> (eigenvalue ±1)

$$C\,|\gamma\rangle = -|\gamma\rangle \qquad C\,|\pi^0\rangle = +|\pi^0\rangle$$

P: Parity

Reflects a system through the origin

- $\boldsymbol{x} \longrightarrow -\boldsymbol{x}$ and $\boldsymbol{p} \longrightarrow -\boldsymbol{p}$
- but $\boldsymbol{L} \longrightarrow \boldsymbol{L}$

Helicity flips

Particles have intrinsic parity:

$$P\,|\gamma\rangle = -|\gamma\rangle \qquad P\,|\pi^0\rangle = -|\pi^0\rangle$$

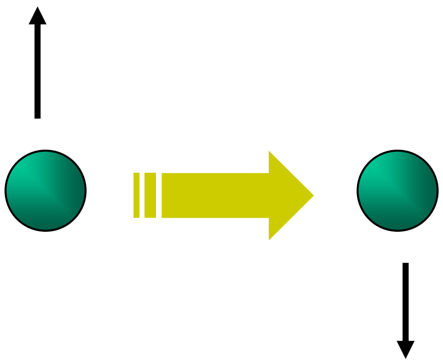
Fermions: opposite parity for particle and antiparticle

Bosons: same parity for particle and antiparticle

T: Time Reversal

Reverses direction of time

- $t \longrightarrow -t$
- $\boldsymbol{p} \longrightarrow -\boldsymbol{p}$



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)

Historical Background

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 β decay of Cobalt.
- Later observed in many other systems (neutrinos, etc.).

Violation of C and P in Weak Decays

Neutrino system:

$$\left.\begin{array}{l} \nu_L \xrightarrow{C} \overline{\nu}_L \\ \nu_L \xrightarrow{P} \nu_R \end{array}\right\}$$

Neither of these states are observed in nature

Example $\Rightarrow$ Pion decay:

$$\Gamma(\pi^+ \to \mu^+ \nu_L) \neq \Gamma(\pi^- \to \mu^- \overline{\nu}_L) = 0$$ C violation

$$\Gamma(\pi^+ \to \mu^+ \nu_L) \neq \Gamma(\pi^+ \to \mu^+ \nu_R) = 0$$ P violation

Conservation of *CP*?

- For a long time it was thought that *CP* was conserved in weak interactions:

$$\Gamma(\pi^+ \to \mu^+ \nu_L) \quad = \quad \Gamma(\pi^- \to \mu^- \overline{\nu}_R)$$

$\Rightarrow$ *CP* 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* <u>even</u> (eigenvalue +1)

$K_2^0 \rightarrow$ long lifetime, *CP* <u>odd</u> (eigenvalue -1)

$$\tau(K_1^0 \rightarrow 2\pi) = 0.9 \times 10^{-10} \text{ sec}$$

$$\tau(K_2^0 \rightarrow 3\pi) = 0.5 \times 10^{-7} \text{ sec}$$

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

$$\left.\begin{array}{l} |K_L^0\rangle = |K_2\rangle + \varepsilon |K_1\rangle \\ |K_S^0\rangle = |K_1\rangle - \varepsilon |K_2\rangle \end{array}\right\} \quad |\varepsilon| \approx 2 \times 10^{-3}$$

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 $\overline{B}$ decay rates
  - Colliders of e^+ and e^- beams → production of $B\overline{B}$ 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)

$$\mathcal{A}_{CP} = \frac{\Gamma(\overline{B} \to \overline{X}) - \Gamma(B \to X)}{\Gamma(\overline{B} \to \overline{X}) + \Gamma(B \to X)}$$

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

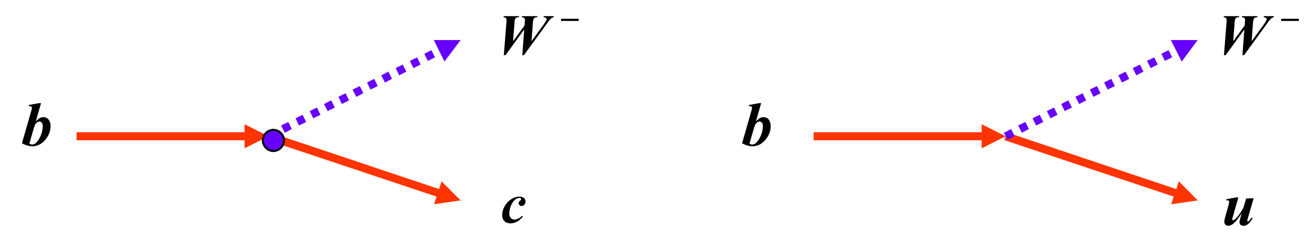
$$\Gamma(\overline{B} \to \overline{X}) \propto |\overline{A}_{\overline{X}}|^2$$

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

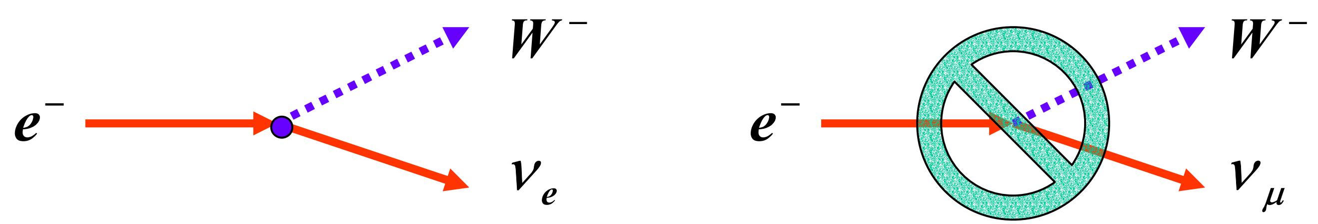
- $\mathcal{A}_{\mathrm{CP}} \neq 0$ is violation of *CP* conservation

The SM Weak Decays

Quark "generation" can change in weak decays
(quark mixing):

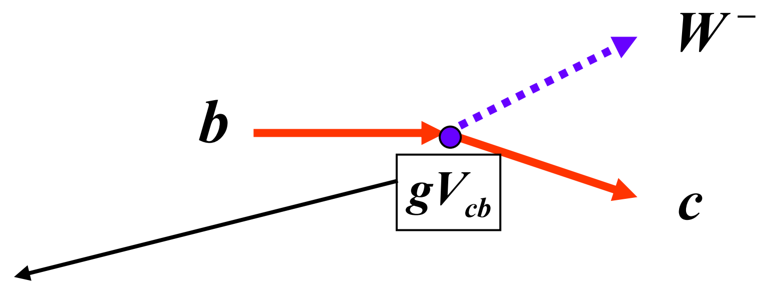


Not so for leptons:



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)

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

- $V_{ij} \Rightarrow V_{ij}^{*}$ 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 ($V^\dagger V = 1$)
- This means 4 independent parameters describe it:
  - 3 real numbers
  - 1 complex phase $\rightarrow$ possibility of *CP* violation

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

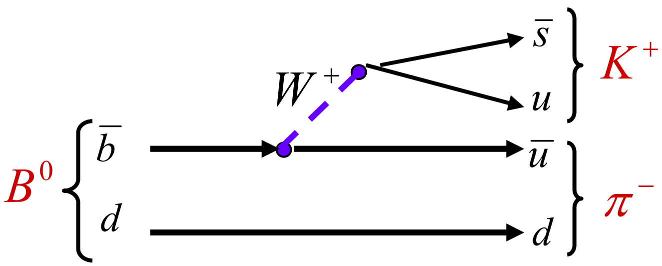
$V_{ub} \rightarrow |V_{ub}|e^{-i\gamma}$

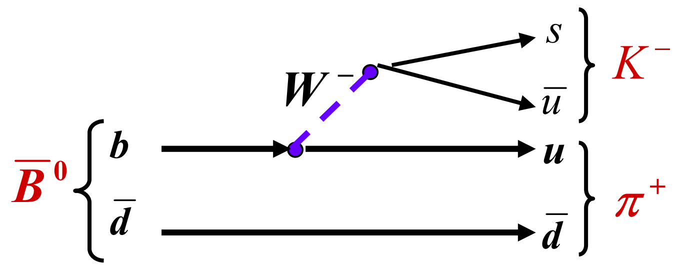
$V_{td} \rightarrow |V_{td}|e^{-i\beta}$

All elements other than V_{td} and V_{ub} are real

CPV in *B* Decays: Example

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





$$A_{K^+\pi^-} = \left|A_{K^+\pi^-}\right| e^{-i\gamma} e^{i\delta}$$

$$\overline{A}_{K^-\pi^+} = \left|\overline{A}_{K^-\pi^+}\right| e^{+i\gamma} e^{i\delta} = \left|A_{K^+\pi^-}\right| e^{+i\gamma} e^{i\delta}$$

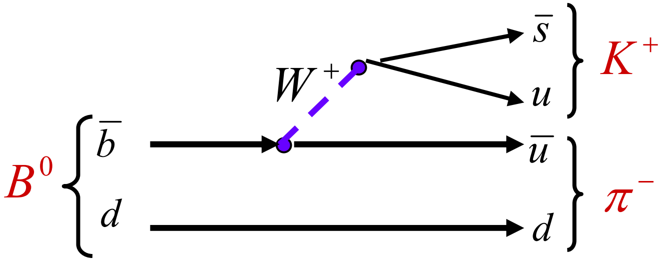
γ is the phase from V_{ub}

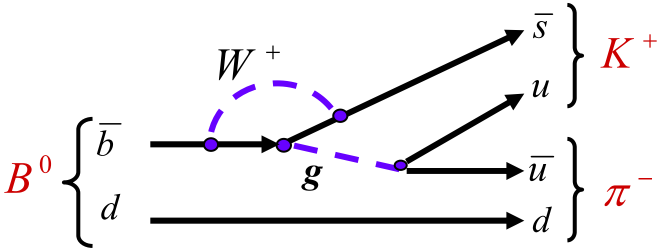
δ is any phase from "strong interactions"

$\mathcal{A}_{CP}$ = 0 since $\left|\overline{A}_{K^-\pi^+}\right|^2 = \left|A_{K^+\pi^-}\right|^2$

CPV in *B* Decays: Example

- But what if a second diagram exists…?





$$A^T_{K^+\pi^-} = \left|A^T_{K^+\pi^-}\right| e^{i(-\gamma+\delta_T)}$$

$$A^P_{K^+\pi^-} = \left|A^P_{K^+\pi^-}\right| e^{i\delta_P}$$

Tree

Penguin

$$A_{K^+\pi^-} = A^T_{K^+\pi^-} + A^P_{K^+\pi^-} = \left|A^T_{K^+\pi^-}\right| e^{i(-\gamma+\delta_T)} + \left|A^P_{K^+\pi^-}\right| e^{i\delta_P}$$

$$\overline{A}_{K^-\pi^+} = \overline{A}^T_{K^-\pi^+} + \overline{A}^P_{K^-\pi^+} = \left|A^T_{K^+\pi^-}\right| e^{i(\gamma+\delta_T)} + \left|A^P_{K^+\pi^-}\right| e^{i\delta_P}$$

CPV in *B* Decays: Example

- Now a non-zero *CP* asymmetry <u>can</u> be possible in SM!

$$\mathcal{A}_{CP} = \frac{\Gamma\left(\overline{B}^0 \to K^-\pi^+\right) - \Gamma\left(B^0 \to K^+\pi^-\right)}{\Gamma\left(\overline{B}^0 \to K^-\pi^+\right) + \Gamma\left(B^0 \to K^+\pi^-\right)}$$

$$\equiv \frac{\left|\overline{A}_{K^-\pi^+}\right|^2 - \left|A_{K^+\pi^-}\right|^2}{\left|\overline{A}_{K^-\pi^+}\right|^2 + \left|A_{K^+\pi^-}\right|^2}$$

$$= \frac{2\left|A_T\right|\left|A_P\right|\sin\gamma\sin\left(\delta_T - \delta_P\right)}{\left|A_T\right|^2 + \left|A_P\right|^2 + 2\left|A_T\right|\left|A_P\right|\cos\gamma\cos\left(\delta_T - \delta_P\right)}$$

$\neq 0$ if:

$\gamma \neq 0, \pi/2$

$\delta_T - \delta_P \neq 0, \pi/2$

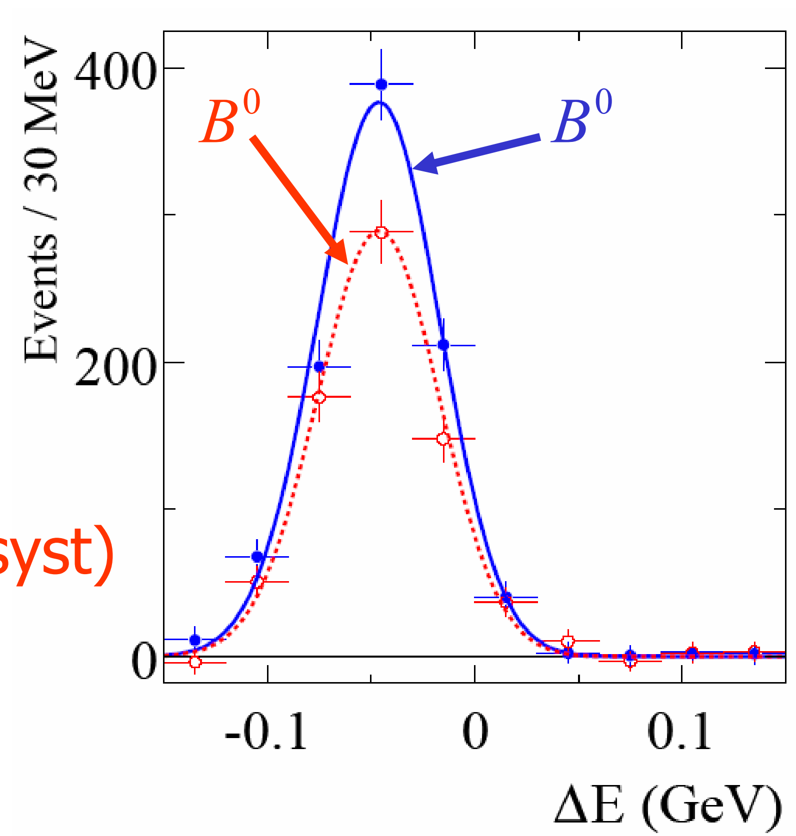
CPV in *B* Decays: Example

- 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

$\mathcal{A}_{CP}$ = -0.133±0.030(stat)±0.009(syst)



CPV in *B* Decays: Example

- 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 β and γ

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

- A "cleaner" way involves measurements of *indirect CP* violation $\Rightarrow$ 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?