An Introduction to CP Violation

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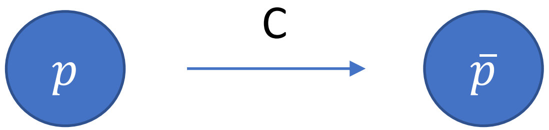
IJC Lab

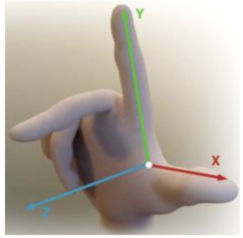

Antimatter
Matter

Introduction: CPT Symmetry

1. C: Charge Conjugation Operator - particle to antiparticle



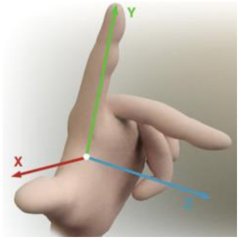
2. P: Parity Operator - point inversion

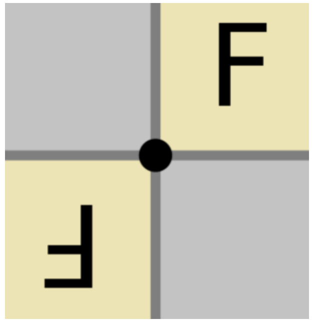


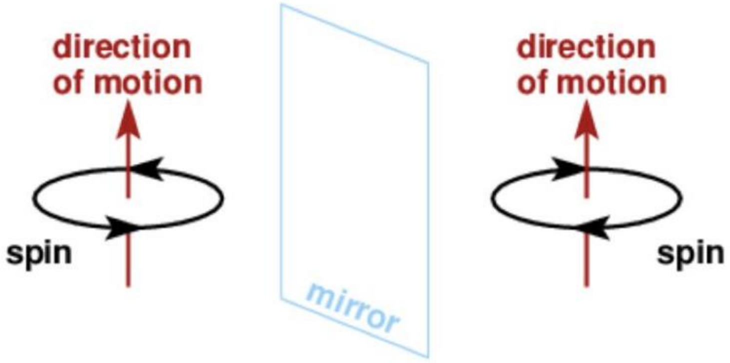
$$(x, y, z) \xrightarrow{P} (-x, -y, -z)$$

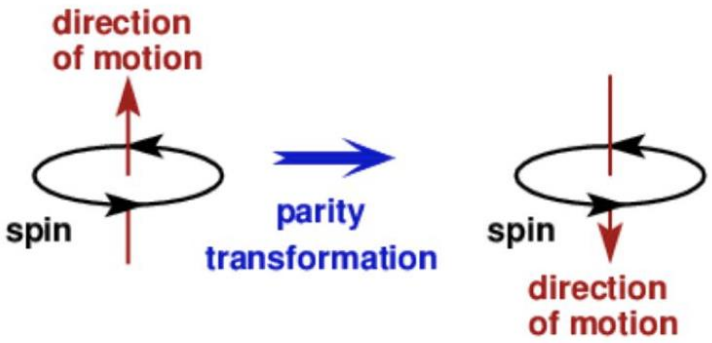
Right-Handed

Left-Handed









<u>Polar Vectors</u>

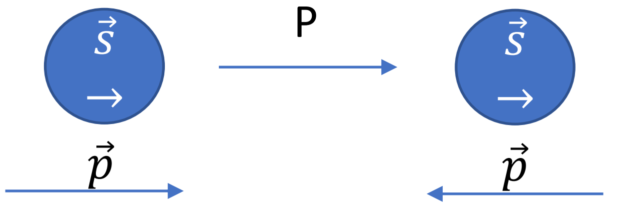
Position: $\vec{r} \rightarrow -\vec{r}$

Linear Momentum: $\vec{p} \rightarrow -\vec{p}$

<u>Axial Vectors (Pseudovectors)</u>

Spin: $\vec{s} \rightarrow \vec{s}$

Angular Momentum: $\vec{L} \rightarrow \vec{L}$



Right-Handed particle

Left-Handed particle

3. T: Time Reversal Operator

CPT is a well respected symmetry of physics

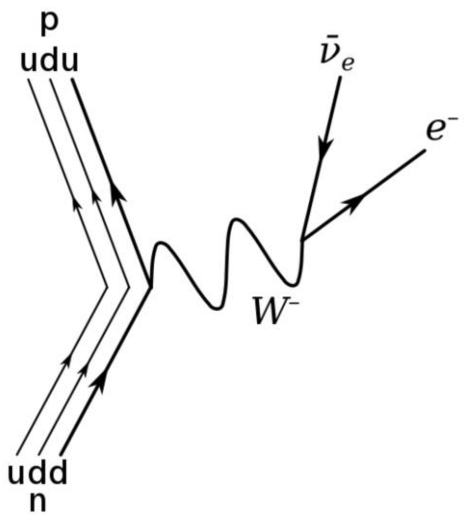
Parity Violation

Chien-Shiung Wu

1956: Chien-Shiung Wu et al. designed an experiment to see Co-60 β-decay.

$$Co_{27}^{60}(5) \rightarrow Ni_{28}^{*60}(4) + e^{-}\left(\frac{1}{2}\right) + \bar{\nu}_e\left(\frac{1}{2}\right)$$

$$Ni_{28}^{*60} \rightarrow Ni_{28}^{60} + 2\gamma$$



Cobalt polarised by magnetic field along z-axis

z-axis

$\bar{\nu}_e$	Co	e^-
LH	rest	RH

Not observed ✗

Parity

e^-	Co	$\bar{\nu}_e$
LH	rest	RH

Observed ✓

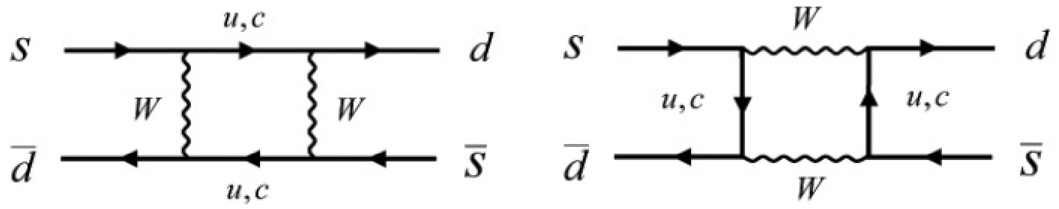
Parity is violated by weak interaction!

Discovery of CP Violation

$K^0(\bar{s}d)$ and $\bar{K}^0(\bar{d}s)$ are flavour eigenstates, which mixes/oscillates via weak intereaction:

Mass eigenstates:
(physical states)

$$|K_1\rangle \equiv \frac{1}{\sqrt{2}}(|K^0\rangle + |\bar{K}^0\rangle)$$
$$|K_2\rangle \equiv \frac{1}{\sqrt{2}}(|K^0\rangle - |\bar{K}^0\rangle)$$



$K^0 - \bar{K}^0$ oscillation

CP eigenstates:

$$CP|K^0\rangle = |\bar{K}^0\rangle$$

$CP|K_1\rangle = +|K_1\rangle$ (CP-even state)
$CP|K_2\rangle = -|K_2\rangle$ (CP-odd state)

$CP|\pi\pi\rangle = +|\pi\pi\rangle$ (CP-even state)
$CP|\pi\pi\pi\rangle = -|\pi\pi\pi\rangle$ (CP-odd state)

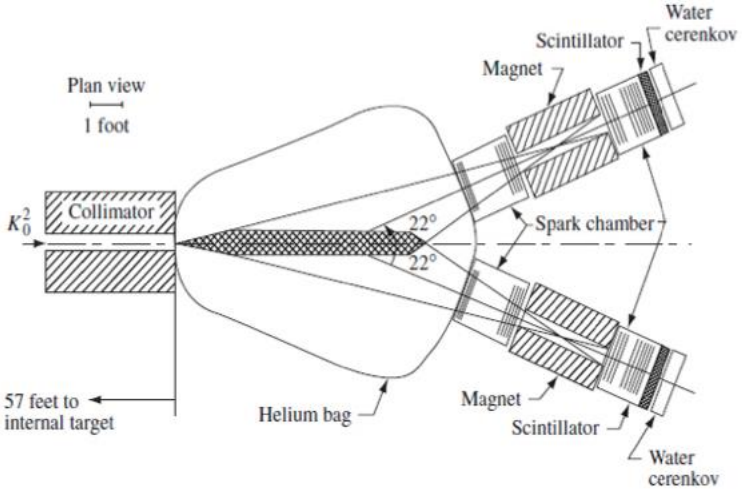
$K_1 \rightarrow 2\pi$
$K_2 \rightarrow 3\pi$

But $M(K_2) \approx 500MeV$ and $M(3\pi) \approx 420\ MeV$
– limited phase space for decay!

$$\tau(K_2) \approx 100\ \tau(K_1)$$

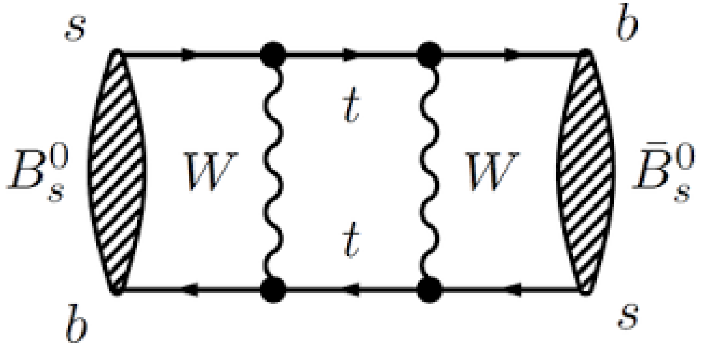
1964: Fitch-Cronin Experiment

Observed $K_2 \rightarrow 2\pi$!
(CP-odd state decaying
to CP-even state)



First evidence of CP-violation found in neutral kaon decays

Types of CP Violation



1. CP violation in oscillation/mixing: *superweak CP violation*

$$|B_1\rangle \equiv (\mathrm{p}|B_s^0\rangle + \mathrm{q}|\bar{B}_s^0\rangle)$$
$$|B_2\rangle \equiv (\mathrm{p}|B_s^0\rangle - \mathrm{q}|\bar{B}_s^0\rangle)$$

$\frac{q}{p} \neq 1$: condition for superweak CP violation

2. CP violation in decay: *direct CP violation*

$$|A(B \to f)| \neq |\bar{A}(\bar{B} \to \bar{f})|$$

3. CP violation in interference of decay and mixing: *mixing-induced CP violation*

$$Im\left(\frac{q}{p}\bar{\rho}_f\right) = |\frac{q}{p}\bar{\rho}_f|\ \sin(\arg(\frac{q}{p}) + \arg(\bar{\rho}_f)) \neq 0$$

$$\bar{\rho}_f = \frac{\bar{A}_f}{A_f}$$

CP Violation in decay: Theory overview

Consider two CP conjugate amplitude:

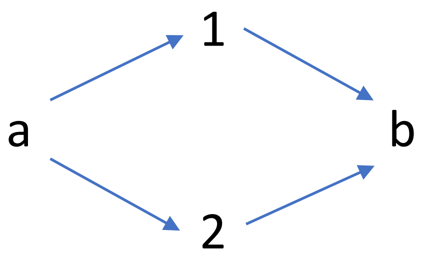
$$a \to b:\ M = |M| e^{i\delta} e^{i\phi}$$
$$\bar{a} \to \bar{b}:\ \bar{M} = |M| e^{i\delta} e^{-i\phi}$$

ϕ: CP-odd phase / CP-violating phase
-change sign on CP conjugation
δ: CP-even phase / CP-conserving phase
-doesn't change sign on CP conjugation

Observables depend on modulus square of amplitude : $|M|^2 = |\bar{M}|^2$

Introduce intermediate states: $a \to 1 \to b$ and $a \to 2 \to b$

$$M = |M_1| e^{i\phi_1} e^{i\delta_1} + |M_2| e^{i\phi_2} e^{i\delta_2}$$
$$\bar{M} = |M_1| e^{-i\phi_1} e^{i\delta_1} + |M_2| e^{-i\phi_2} e^{i\delta_2}$$



Observable "CP Asymmetry"

$$|\bar{M}|^2 - |M|^2 = -4|\mathrm{M}_1||\mathrm{M}_2| \sin(\phi_1 - \phi_2) \sin(\delta_1 - \delta_2)$$

Essential conditions to 'observe' CP violation in decay ?

1. Two interfering amplitudes
2. Different CP-odd phase
3. Different CP-even phase

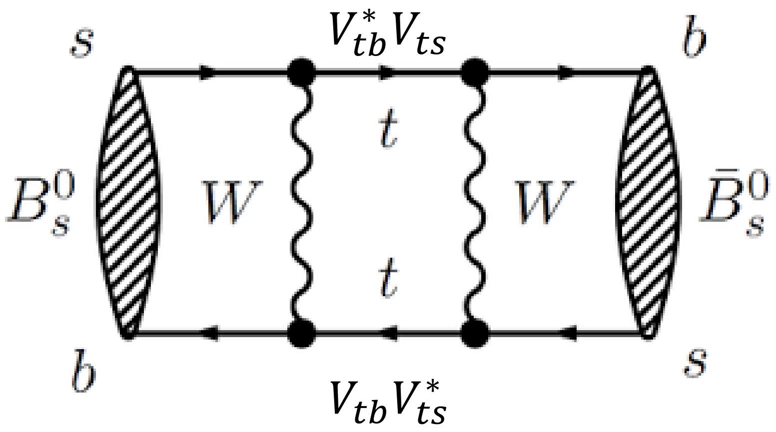
Source of CP violation in SM:
CP-odd phase in CKM Matrix

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

CP violation in $B_s^0 \to \phi\phi$

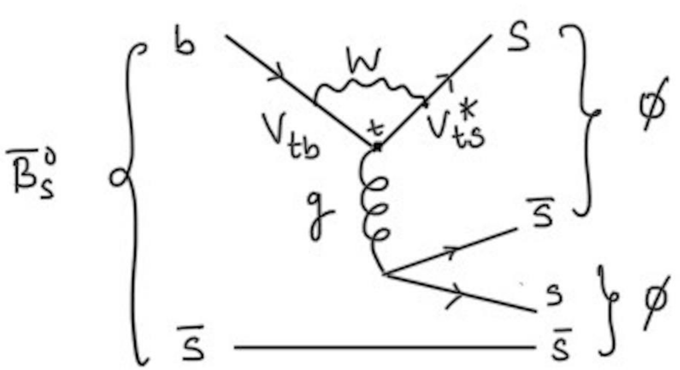
CPV phase in oscillation amplitude : $B_s^0 - \bar{B}_s^0$ oscillation

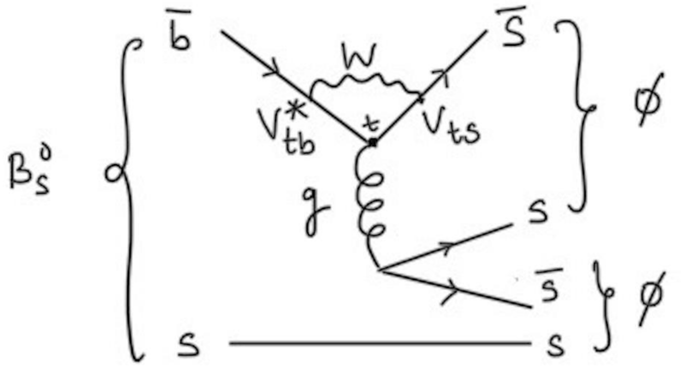
$$\frac{q}{p} = \frac{V_{tb}^* V_{ts}}{V_{tb} V_{ts}^*}$$



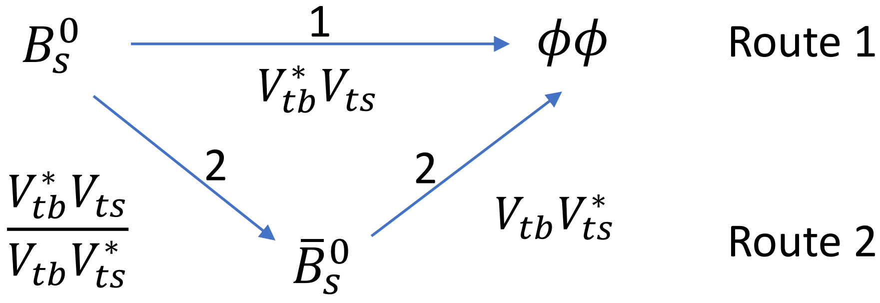
CPV phase in decay amplitude: $B_s^0 \to \phi\phi$ decay

$$M(B_s^0 \to \phi\phi) \propto V_{tb}^* V_{ts}$$
$$\bar{M}(\bar{B}_s^0 \to \phi\phi) \propto V_{tb} V_{ts}^*$$





Interference in decay and mixing



CP-violating phase in interference:

$$\frac{q}{p}\,\bar{\rho}_{\phi\phi} = \frac{q}{p}\frac{\bar{M}}{M} = \frac{V_{tb}^* V_{ts}}{V_{tb} V_{ts}^*}\,\frac{V_{tb} V_{ts}^*}{V_{tb}^* V_{ts}} = 1$$

i.e the decay and oscillation amplitude CP-violating phase cancel out each other!

Summary

- CP Violation in SM: complex phase in CKM Matrix
- Matter-Antimetter asymmetry: more CP violation required
- Three types of CP violation: mixing, decay and decay+mixing
- CP observables: probe for new physics

”Thank you for your attention ☺ ”