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SUMMER SCHOOL ON PARTICLE PHYSICS

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CP VIOLATION AND B-PHYSICS

Lecture I

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Please note: These are preliminary notes intended for internal distribution only

Plan of lectures

1. (today)

- C P and T symmetries
- The role of gauge invariance and hermiticity
- Quantum mechanics of neutral mesons (K, D & B)
  - a) with CP symmetry
  - b) CP symmetry violations
- 3 types of CP Violation

Lecture 2 (DIRAC LECTURE)

Instantons and Strong CP violation

- What is an instanton?

- Multiple vacua and boundary conditions $\Rightarrow \theta F\tilde{F}$

- A cosmological question
  $\Rightarrow$ PQ symmetry

- Axions, old and new (invisible)

- Axion searches

Lecture 3 **Standard Model Predictions for CP Violation in B Decays**

- CKM Unitarity
  - CP conserving constraints
- Time-dependendent amplitudes
  - Possible quark-level decays
  - Some sample channels
    - $B_d \to \psi K_S$
    - $B_s \to DK$
    - $B_d \to \phi K_S$
    - $B_d \to \pi^+ \pi^-$

Lecture (4) Tools of the Trade in B-decay physics

- Trees and Penguins ⇒ Operator Product Expansion

- Factorization (old & new)

- Heavy Quark Expansion

- Isospin and SU(3) symmetry

- Lattice calculations

- QCD sum rule input

Lecture 5. B experiments

1. CLEO symmetric e^+e^- collider

2. the B Factories Belle + BaBar
   asymmetric e^+e^- collisions

3. TeVatron B physics @ CDF + D0

4. the next generation hadron collider exp.
   LHCB and BTeV

5. ? - the future

Philosophy

In 5 lectures (including DIRAC lecture)

I cannot teach all the details

I will be schematic about equations
+ references to more detailed treatments

I will stress the CONCEPTS
and their APPLICATIONS

→ LISTEN + THINK
- dont take notes

→ ASK QUESTIONS
- anytime

Lecture 1

The Basics

Symmetry

↕

Invariance of $\mathcal{L}$

↕

Conservation laws

Quantum # state labels

Local

Continuous

Discrete

Global

Co-ordinate Invariances

Gauge Invariances

Discrete Invariances $\rightarrow$ C , P , T

Field Transformations

$$\psi \to C \to -i\left(\bar{\psi}(t,x)\gamma_0\gamma^2\right)^T$$

$$\psi \to P \to \gamma^0 \psi(t,-x)$$

$$\psi \to T \to -\gamma_1\gamma_3 \psi(-t,x)$$

Terms in $\mathcal{L}$

CP

$$\bar{\psi}_i \psi_j \longrightarrow \bar{\psi}_j \psi_i$$

$$i\bar{\psi}_i \gamma_5 \psi_j \longrightarrow -i\bar{\psi}_j \gamma^5 \psi_i$$

$$\partial^\mu \bar{\psi}_i \gamma_\mu \psi_j \longrightarrow -\partial_\mu \bar{\psi}_j \gamma^\mu \psi_i$$

$$\partial^\mu \bar{\psi}_i \gamma_\mu \gamma_5 \psi_j \longrightarrow -\partial_\mu \bar{\psi}_j \gamma^\mu \gamma_5 \psi_i$$

$$A^\mu \bar{\psi}_i \gamma_\mu \psi_j \longrightarrow A \bar{\psi}_j \gamma^\mu \psi_i$$

$$A^\mu \bar{\psi}_i \gamma_\mu \gamma_5 \psi_j \longrightarrow A_\mu \bar{\psi}_j \gamma^\mu \gamma_5 \psi_i$$

An intuitive idea of CP Violation

$$\mathcal{A}(A \to B) \overset{CP}{\Longleftrightarrow} \pm \mathcal{A}(\bar{A} \to \bar{B})$$

A, B: states — $\bar{A}$, $\bar{B}$: CP conjugate states

Note CPT $\Rightarrow$ $\Gamma_{tot}(A) = \Gamma_{tot}(\bar{A})$

When can we get CP violation?

If

$$\mathcal{A}(A \to B) = g_1 (r_1 e^{i\phi_1}) + g_2 (r_2 e^{i\phi_2})$$

g_1: coupling — $r_1 e^{i\phi_1}$: matrix element for transition

Then

$$\mathcal{A}(\bar{A} \to \bar{B}) = g_1^* (r_1 e^{i\phi_1}) + g_2^* (r_2 e^{i\phi_2})$$

"Strong" Phases ϕ_1 and ϕ_2 from absorbtive parts in sum over intermediate states

same for particles & antiparticles

Now in general:

$$|A|^2 - |\bar{A}|^2 = \text{Re}\left[g_1 g_2^* \, r_1 r_2 \, e^{i(\phi_1 - \phi_2)}\right] - \text{Re}\left[g_1^* g_2 \, r_1 r_2 \, e^{i(\varphi_1 - \varphi_2)}\right]$$

$$= 2\,\text{Im}\left(g_1 g_2^*\right) \text{Im} \; r_1 r_2 \, e^{i(\varphi_1 - \varphi_2)}$$

$$= \text{Im}\left(g_1 g_2^*\right) r_1 r_2 \sin\left(\varphi_1 - \varphi_2\right)$$

↑ Difference of coupling phases

→ Rephasing invariant!

Difference of "strong" phases

→ "Direct" CP Violation

Hermiticity of $\mathcal{L}$

$$g_{ij} \bar{\psi}_i (\ ) \psi_j + g^*_{ij} \bar{\psi}_j (\ )^* \psi_i$$

CP Invariance is obvious if $g = g^*$
i.e. all real couplings

Rephasing $\psi_i \to e^{i\alpha_i} \psi_i$

is equivalent to $g_{ij} \to g_{ij} e^{-i(\alpha_i - \alpha_j)}$

$\Longleftrightarrow$ choose a different definition of C

So the question is whether there is
any choice of CP transformation
that leaves $\mathcal{L}$ invariant

$\Longleftrightarrow$ any set of rephasing of fields
that makes all g's and m's real.

QED

$$\bar{\psi}_i \left(\partial^\mu + i g A^\mu \right) \gamma_\mu \psi_j \quad + h.c.$$

↑ gauge invariance

particle conservation laws $\Rightarrow$ $i = j$

then hermiticity $\Rightarrow$ $g = g^*$

Mass term

Hermiticity $\Rightarrow$ $m_R \bar{\psi}\psi + i\, m_I \bar{\psi}\gamma_5\psi$

Rephasing $\psi \to e^{i\alpha\gamma_5}\psi$

$\Rightarrow$ Real m

Gauge Invariance + Particle # conservation

+ Hermiticity + Rephasing Invariance

$\Rightarrow$ Automatic CP Conservation

How can CP violating couplings appear?

<u>An example</u>

$$Y_{ijk}\varphi_k \bar{\psi}_i \psi_j \quad + Y^*_{ijk}\varphi^*_k \bar{\psi}_j \psi_i$$

↑ hermeticity

→ For complex φ Y_{ijk} need not be real

→ For $i \neq j$ Y_{ijk} need not be real

? Can rephasing remove complex Y's?

→ depends on numbers of ψ_i, φ_k

→ with enough types of each some complex y's survive

Quantum Mechanics of Neutral Mesons

Flavor Eigestates

$M^0 = \bar{q}\, q'$ $\qquad$ $\overline{M^0} = \bar{q}'\, q$

e.g. $K^0 = \bar{s}\, d$ $\qquad$ $\overline{K^0} = \bar{d}\, s$

$D^0 = \bar{u}\, c$ $\qquad$ $\overline{D^0} = \bar{c}\, u$

$B^0 = \bar{b}\, d$ $\qquad$ $\overline{B^0} = \bar{d}\, b$

$B_s^0 = \bar{b}\, s$ $\qquad$ $\overline{B_s^0} = \bar{s}\, b$

CP Eigenstates

$$\frac{M^0 \pm \overline{M^0}}{\sqrt{2}}$$

$\Leftarrow$ Eigenstates of $\mathcal{H}$ if $[CP, \mathcal{H}] = 0$

CP symmetry

$\Rightarrow$ Particles with definite mass and lifetime

Gell-Mann & Pais 1955

Production via flavor conserving (strong or em) processes

→ production in pairs $\Delta S = 0$

e.g. $\pi^0 + p \to n + K^0 + K^-$

In modern quark language $\bar{s}d$ $\bar{u}s$

BUT Propagation as CP eigenstates ⟺ mixing

Decay via weak processes

→ Time dependent rates for flavor-labelled decays e.g. $K \to \pi \ell \nu$

→ Decays to CP eigenstates → two distinct lifetimes

CP even → $\pi\pi$ short lived

CP odd ↛ $\pi\pi$ longer-lived

But

$K_L \rightarrow \pi\pi$ (1964)

Christenson Cronin Fitch & Turlay

$\Rightarrow$ CP symmetry is not exact.

Mass eigenstates

$\neq$ CP Eigenstates

- Production as flavor eigenstates
- Propagation and decay as mass eigenstates

Mass differences and lifetime differences

$$\mathcal{M}_1 = p M^0 + q \bar{M}^0 \qquad m_1 \; \Gamma_1$$

$$\mathcal{M}_2 = p M^0 - q \bar{M}^0 \qquad m_2 \; \Gamma_2$$

$$m = \frac{m_1 + m_2}{2} \qquad \Delta m = \frac{m_1 - m_2}{2}$$

$$\Gamma = \frac{\Gamma_1 + \Gamma_2}{2} \qquad \Delta \Gamma = \frac{\Gamma_1 - \Gamma_2}{2}$$

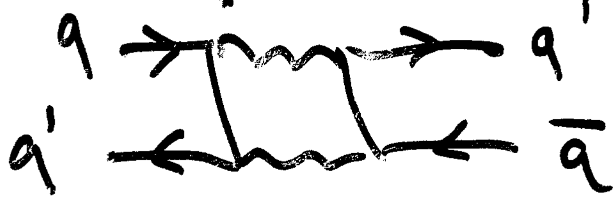
My Convention: $\Delta m > 0$

N.B. There are other conventions floating around **BEWARE**

"Mixing"

Standard Model Version

e.g.



Mass and Mixing matrix

$$\Omega = M + i\Gamma$$

Both M & Γ can be complex

M – hermitian matrices
Γ – anti-hermitian

$$q/p = -\left(\frac{\Delta m - i/_2\, \Delta\Gamma}{2(M_{12} - i/_2\, \Gamma_{12})}\right)$$

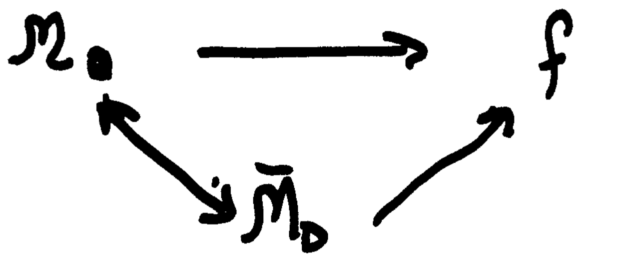
$$= -2\left(\frac{M_{12}^* - i/_2\, \Gamma_{12}^*}{\Delta m - i/_2\, \Delta\Gamma}\right)$$

Note

$$\langle B_L | B_H \rangle = pp^* - qq^*$$

$\neq 0$ unless $|p| = |q| = \frac{1}{\sqrt{2}}$ or $\left|\frac{q}{p}\right| = 1$.

Physics of decays:



CP eigenstate ↓

⇐ If $\bar{f} = \pm f$ then 2 paths can interfere

We will find CP violation is governed by

$$\lambda = \frac{q}{p} \frac{\bar{A}(\bar{M} \to \bar{f})}{A(M \to f)}$$

$\lambda = 1$ no CP Violation

- $|q/p| \neq 1$ CP Violation in mixing
- $\left|\frac{\bar{A}}{A}\right| \neq 1$ CP Violation in decay
- $\arg \lambda \neq 0$ CP Violation in interference of decay with and without mixing