Title: Particle Physics Lecture - 230324

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Collection: Particle Physics (2022/2023)

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Lecture 10. strong CP problem & Axion.

1-Family:

$$\mathcal{L}_{SM} \supset Q^\dagger \not{D} Q + U_c^\dagger \not{D} U_c + D_c^\dagger \not{D} D_c$$

$$+ yHQU_c + yH^\dagger Q D_c$$

$$\Rightarrow Q^\dagger \not{D} Q + Q_c^\dagger \not{D} Q_c + \underline{M Q Q^c}$$

$$Q_c = (U_c, d_c)$$

Kinetic terms: $U(2)_L \times U(2)_R \rightarrow \underline{SU(2)}_V \times SU(2)_A \times U(1)_B \times U(1)_A$

$SU(2)_A$ breaking: $\langle Q Q^c \rangle$ spontaneous @ $F \sim f_\pi \sim 100$ MeV

M: explicitly @ $\epsilon \sim m_u, m_d \sim$ MeV

Spurion Analysis:

treat M as a field.

$\mathcal{L} \supset tr(M\, U)$ gives $m_{\pi^0, \pi^\pm}$

$M \rightarrow 0$ $\quad m_\pi \rightarrow 0$ exact. GB.

$U(1)_B$: $Q \rightarrow Q e^{i\alpha}$ $\quad Q_c \rightarrow Q_c e^{-i\alpha}$

Baryon Number.

$U(1)_A$: $Q \rightarrow Q e^{i\alpha}$, $Q_c \rightarrow Q_c e^{i\alpha}$

(QFT): $Q \to Q e^{i\alpha}$. $Q_c \to Q_c\, e^{i\alpha}$

$\mathcal{L} \to \mathcal{L} + \frac{\alpha_s \cdot \alpha}{4\pi} G\tilde{G}$

we know

$\mathcal{L}_{SM} \supset \frac{\alpha_s\, \theta_{QCD}}{8\pi} G\tilde{G}$

$\begin{cases} Q \to Q e^{i\alpha} \quad Q_c \to Q_c e^{i\alpha} \\ \Theta \to \Theta - 2\alpha \end{cases}$ Non-linearly Realized

if ~~$\alpha_s \to 0$~~

including M:

$\begin{cases} Q \to Q^{i\alpha} \\ \theta \to \theta - 2\alpha \quad Q_c \to Q_c e^{i\alpha} \\ m_u \to e^{-i2\alpha} m_u,\ m_d \to e^{-i2\alpha} m_d \end{cases}$

$Q \to Q e^{i\alpha}$ ...

$\Theta \to \Theta - 2\alpha$

and $M e^{i\theta_M} \to M e^{-i2\alpha} e^{i\theta_M}$

combination

$\bar{\Theta} = \Theta + \theta_{m_u} + \theta_{m_d}$

$=$

$Q_c e^{-i\alpha}$

$e^{i\alpha}$

QFT: $Q \to Q e^{i\alpha}$ $\quad Q_c \to Q_c e^{i\alpha}$

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Non-linearly Realized

if $\cancel{\alpha_s \to 0}$

including M

$$\begin{cases} Q \to Q^{i\alpha} \quad Q_c \to Q_c e^{i\alpha} \\ \theta \to \theta - 2\alpha \\ m_u \to e^{-i2\alpha} m_u, \; m_d \to e^{-i2\alpha} m_d \end{cases}$$

$e^{-i\alpha}$

$Q \to Q e^{i\alpha}$ ...

$\theta \to \theta - 2\alpha$

and $M e^{i\theta_M} \to M e^{-i2\alpha} e^{i\theta_M}$

combination

$\bar{\theta} = \theta + \theta_{m_u} + \theta_{m_d}$

$\bar{\theta} = \theta_{QCD} + \arg\det M$

All physical angle that does not change with field redefination has experimental consequences.

Measurement: $\vec{I} = \vec{r} \times \vec{p}$ $\quad \vec{d} = e\vec{r}$

Parity: $\vec{x} \to -\vec{x}$

CP = Time reversal ($CPT = 1$)

$t \to -t$

$\vec{s} \cdot \vec{d} \neq 0$ violates both P & CP

In the SM: neutron $d_N \sim \theta \, e \, R_{\text{Neutron}} \sim e \cdot \theta \cdot \text{fm}$.

$\cancel{P}$ and $\cancel{CP}$

$d_N < 10^{-26}\, e \cdot \text{cm} \Rightarrow \boxed{\bar{\theta} \le 10^{-11}} \Rightarrow$ P & CP should be good symmetries of QCD

On the other hand. Claudia.

$\cancel{P}$: Wu ^{60}Co decay.

$\cancel{CP}$: CKM.

are violated by weak interactions.

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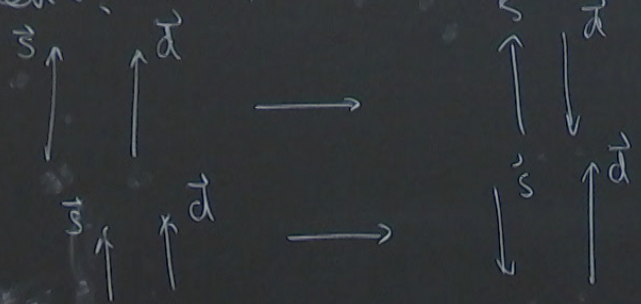

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Solutions:

① $m_q = 0$ $(m_u = 0)$

② QCD axions.

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Parity: $\vec{x} \to -\vec{x}$

$\vec{s}\uparrow \ \uparrow\vec{d} \longrightarrow \vec{s}\uparrow \ \downarrow\vec{d}$

$\vec{s}\uparrow \ \uparrow\vec{d} \longrightarrow \vec{s}\downarrow \ \uparrow\vec{d}$

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$\left\{ \begin{array}{l} \cancel{P}: \text{Wu } {}^{60}\text{Co decay.} \\ \cancel{CP}: \text{CKM} \end{array} \right.$

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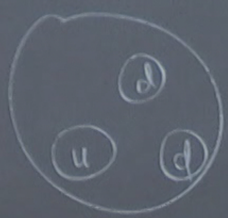
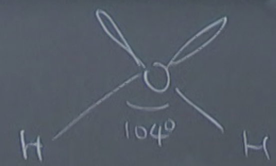


$AB_2 \Rightarrow \begin{cases} H_2O \\ CO_2 \end{cases}$



$d \neq 0$

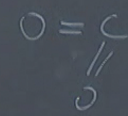
O = C = O

$d = 0$

$\theta_{CO_2} = 180°$

① θ_{CO_2} dynamical varible

② $\theta_{CO_2} = 180°$ is a minimum.



$\Rightarrow$ O = C = O

H − O − H

$\Rightarrow$ ① $\bar{\theta} \rightarrow$ dynamical variable. field (Axion)

② Make sure $\bar{\theta} = 0$ is the minimum.

we sho

$\bar{\theta} = 0$

② $E(\theta) = \mathrm{tr}(MU)$

$$= -m_\pi^2 f_\pi^2 \sqrt{\cos^2\frac{\theta}{2} + \left(\frac{m_u - m_d}{m_u + m_d}\right)^2 \sin^2\frac{\theta}{2}}$$

$$\cdot \cos\left(\frac{\pi^0}{f_\pi} - \phi(\theta)\right)$$

$$\sin\phi \equiv \frac{m_d - m_u}{m_d + m_u} \sin\frac{\theta}{2}$$

$$\text{Minimum} \Rightarrow \begin{cases} \cos\left(\frac{\pi^0}{f_\pi} - \phi(\theta)\right) = 1 \\ \sqrt{\ } \rightarrow \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\frac{\theta}{2}} \end{cases}$$

$\left(\theta = 0 \Rightarrow \sqrt{\ } = 1 \text{ is the maximum}\right)$

we showed:

$\bar{\theta} = 0$ is indeed the minimum.

Back to $m_u = 0$

If m_u or $m_d = 0$, $\sqrt{} = 1$

and $E(\theta)$ is independent of θ

- - - - - - -

he maximum),