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*SUMMER SCHOOL ON PARTICLE PHYSICS*

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# THE CP PUZZLE IN THE STRONG INTERACTIONS

## DIRAC LECTURE *

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

* **The 2000 Dirac Lectures will be published as part of the ICTP Lecture Notes Series**

# The CP Puzzle

# In the Strong Interactions

**DIRAC LECTURE**

- Thanks to
  - ICTP
  - My collaborators
    - Steve Weinberg
    - Howard Georgi
    - Roberto Peccei

Howard + Jogesh have covered GUT s

My citation added strong CP breaking

so I'll focus on that.

For the non-physicists

CP symmetry

= symmetry between

the laws of physics for matter

↕

the laws of physics for antimatter

Strong interactions

= interactions between quarks

to make protons & neutrons

and between protons & neutrons

to make nuclei

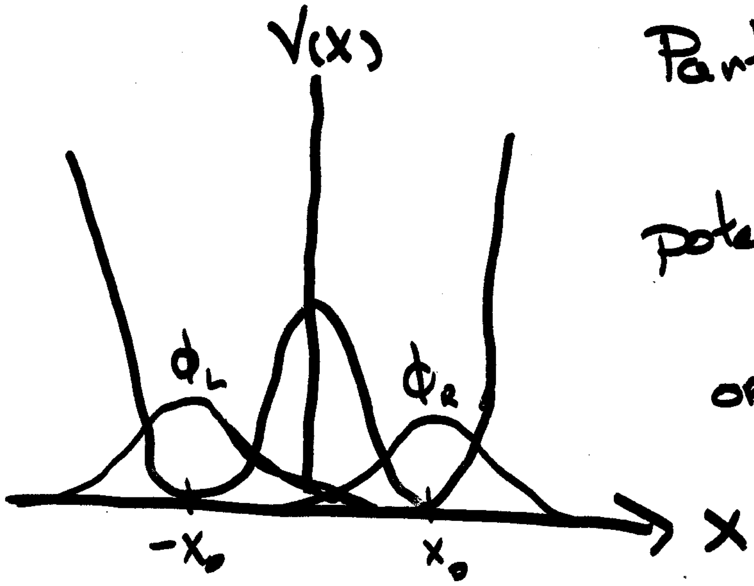
The puzzle:

Strong interactions appear to have CP symmetry

Weak interactions do not.

How can this difference be maintained?

# Review of some basic Quantum Mechanics




Particle in a double well

potential: $V(x) = V(-x)$

OR $P\, V(x)\, P = V(x)$
mirror reflection symmetry

What is the ground state?

Classically either $x = x_0$ or $x = -x_0$

Quantum solutions $\varphi_R = f(x - x_0)$

$\varphi_L = f(x + x_0)$

True ground states

States of definite P symmetry

$$\varphi_{e,o} = \frac{\varphi_R \pm \varphi_L}{\sqrt{2}}$$ ⇐ not quite degenerate

Why: tails overlap ⟺ "tunneling"

tunneling is an "event" ⟺ in field theory an "instanton"

# Similar story in QCD

$$\mathcal{L} = F_{\mu\nu} F^{\mu\nu} + \bar{\psi}(\partial_\mu - i g A^a_\mu \cdot \lambda^a)\psi + m\bar{\psi}\psi$$

(schematically speaking)

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\nu + i g A^b_\mu A^c_\nu f^{abc}$$

$G(\theta)$ = gauge transformation

$$A^a_\mu \to A^a_\mu + \partial_\mu \theta^a$$

$$\psi \to e^{i\theta^a \cdot \lambda^a}\psi$$

$$\boxed{G\mathcal{L} = \mathcal{L}}$$

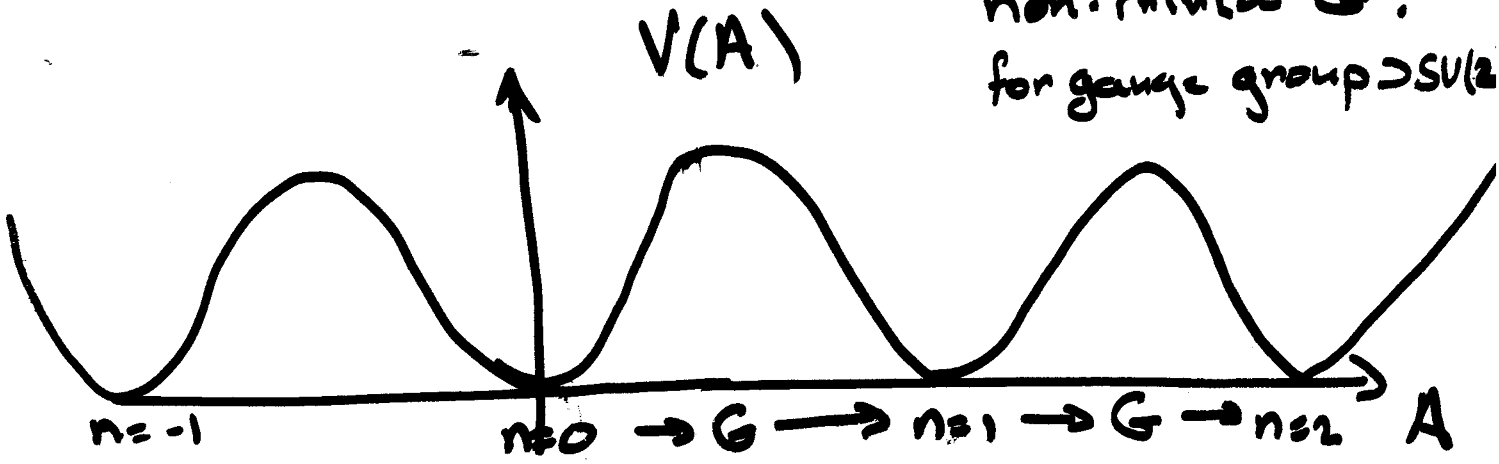
BUT

$$n = \frac{1}{g^2}\int d^4x \; F_{\mu\nu} F_{\rho\sigma} \; \epsilon^{\mu\nu\rho\sigma} = F\tilde{F}$$

$G|n\rangle \to |n+1\rangle$

non-trivial $G$.

for gauge group $\supset SU(2)$



Multiple gauge-equivalent "vacuum" states

Instanton event $\Leftrightarrow$ tunneling

$|n\rangle \to |n+1\rangle$

True ground state **G-invariant**

$$|\theta\rangle = \sum e^{in\theta} |n\rangle \qquad G|\theta\rangle = e^{i\theta}|\theta\rangle$$

Are $\theta$-vacua degenerate?

**Rephasing**

Chiral transformation:

$$\psi \to e^{-i\alpha\gamma_5}\psi \qquad \begin{cases} m \to m - i\alpha \\ \theta_{eff} \to \theta_{eff} + i\alpha \end{cases}$$

$$\theta_{eff} = \theta + \arg\det m$$

For $m=0$ All $\theta$ are equivalent $\Rightarrow$ $\boxed{\theta_{eff}=0}$

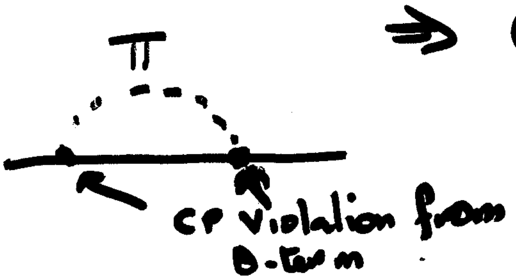
For $m\neq 0$ $\theta_{eff}$ is physical

$$e^{in\theta} = e^{i\frac{\theta}{g^2}\int d^4x\, \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma}}$$

↑ Violates CP symmetry

Modifies effective chiral lagrangian e.g. $\pi N\bar{N}$ coupling

Physical consequence $\quad \frac{m_\pi}{f_\pi}\, \pi \langle \bar{q}\gamma_5 q + i\theta \bar{q} q \rangle$




⇒ electric dipole moment for neutron

Known to be extremely small

↑

Experimental limit ⇒ $\theta \lesssim 10^{-12}$

But once the theory has CP symmetry breaking anywhere how does it avoid having a larger $\theta$ ?

none completely ruled out

3 "solutions"

1. $m_u = 0$ — doesn't seem to be true.
(just possible that bare mass is zero)
induced mass $\sim \frac{m_d m_s}{\Lambda}$, ← ? what $\Lambda$

2. Impose CP symmetry

Spontaneous breaking – soft terms only

Induced $\theta$-term may be small enough
- depends on details of theory
- difficult to achieve

3. Peccei-Quinn symmetry

a way to get automatic
or "natural" $\theta = 0$

$\Longrightarrow$ axion

as pointed out by
Weinberg & Wilczek
(independently)

# A clue from cosmology

In the early universe $\langle \varphi \rangle = 0$

Higgs field expectation value

$\Rightarrow$ $m_q = 0$ for all quarks

$\Rightarrow$ $\theta_{eff} = 0$ independent of $\theta$

I asked:

Can we devise a potential for the Higgs field such that

for any $\theta$

as the universe cools

phases from $\langle \varphi \rangle$ give

$$\theta_{eff} = \theta + \arg \det M = 0$$

as lowest energy solution ?

Answer – YES!

How?

Any theory with added global $U(1)$ symmetry broken only by $\theta F\tilde{F}$ term

<u>Simplest example</u>

Standard model with two Higgs doublets

$\varphi_u$ $\langle \varphi_u \rangle = v_u$ gives up-type quark masses

$\varphi_d$ $\langle \varphi_d \rangle = v_d$ gives down-type masses

Thanks to Sidney Coleman

U(1) symmetry

$$\varphi_u \to e^{i\alpha}\varphi_u \qquad \varphi_d \to e^{-i\alpha}\varphi_d$$

$$\psi_L \to e^{-i\alpha\gamma_5}\psi_L$$

Then:

$$\mathcal{L}_y = y_u\,\varphi_u\,\bar{u}_R\,\psi_L + y_d\,\tilde{\varphi}_d\,\bar{d}_R\,\psi_L + \text{h.c.}$$

Notation: $\varphi = \begin{pmatrix}\varphi_0\\ \varphi^-\end{pmatrix} \qquad \tilde{\varphi} = \begin{pmatrix}\varphi^+\\ \varphi^{0*}\end{pmatrix} \qquad \psi_L = \begin{pmatrix}u_L\\ d_L\end{pmatrix}$

AND

$V(\varphi_u, \varphi_d)$ has no $(\varphi_u \cdot \tilde{\varphi}_d^{*})^n$

Let $\eta = \arg\,(y_u\varphi_u)(y_d\tilde{\varphi}_d^{*})$

then: $V(\varphi_u, \varphi_d)$ appears to be $\eta$ independent

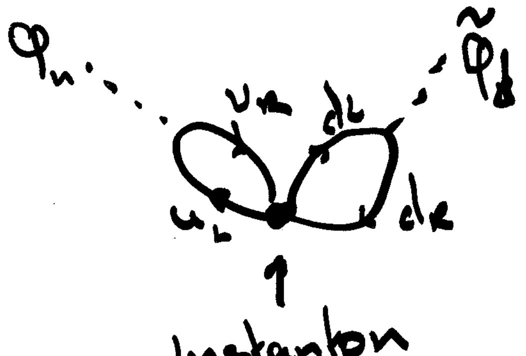
← Sombrero potential)

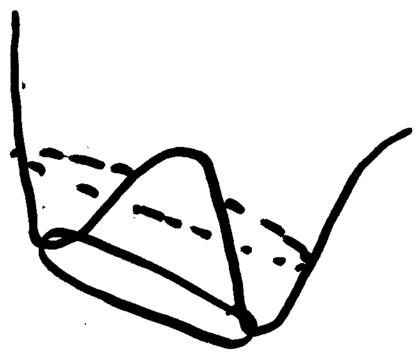
BUT when $\langle \varphi_u \rangle$ $\langle \varphi_d \rangle$ appear

$$\arg \det M = \langle \eta \rangle$$

and $$\theta_{eff} = \theta - \langle \eta \rangle$$

Instanton effects tilt the potential slightly



Sleepy Sombrero

$$V \to V(\theta_{eff})$$

minimizes for $\langle \eta \rangle = \theta$
OR $\theta_{eff} = 0$

Weinberg & Wilczek pointed out

U(1) spontaneously broken

$\Rightarrow$ Goldstone Boson

Tilted U(1) spontaneously broken

$\Rightarrow$ almost Goldstone Boson

= AXION

A light weakly interacting particle

→ lab constraints (direct searches)

→ astrophysical constraints

→ cosmological (dark matter) constraints

→ Simplest version of U(1) ruled out
"Invisible axion" versions survive

- PQ Symmetry remains a possible answer to why $\theta_{eff} = 0$

- Axions still a viable dark matter candidate

- Axion search experiments continue

for some more details see

Thy: M. Dine TASI 2000 lectures hep-ph/0011376

Exp: L. Rosenberg & K. Van Bibber
Physics Reports 325 Issue 1 pp 1-39 (2000)