CP Symmetry Breaking in the Strong Interactions

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Background: What causes CP Violation?

Interference <–> two different coupling phases

$$A(i \to f) = g_1 e^{i\phi_1} a_1 e^{i\delta_1} + g_2 e^{i\phi_2} a_2 e^{i\delta_2}$$
$$A(\bar{i} \to \bar{f}) = g_1 e^{-i\phi_1} a_1 e^{i\delta_1} + g_2 e^{-i\phi_2} a_2 e^{i\delta_2}$$

- ϕ_i phases of couplings—change sign
- δ_i phases of scattering amplitudes—do not change
  - arise from strongly coupled channels

$$|A(i \to f)|^2 - |A(\bar{i} \to \bar{f})|^2 =$$
$$g_1 g_2 \sin(\phi_1 - \phi_2) a_1 a_2 \sin(\delta_1 - \delta_2)$$

- only RELATIVE phases are physical

Context –QED

- In Dirac equation and QED CP symmetry is automatic
- Gauge invariance plus hermiticity
  - makes gauge coupling real
- Fermion mass can be made real by a chiral rotation
  - has no impact on gauge coupling terms

What about QCD?

- Lagrangian looks very similar
- Instantons make a difference
  - Polkakov; 't Hooft
- Many gauge-inequivalent ground states –n-vacua $|n>$
- Instanton is a tunneling event $|n> \longrightarrow |n+1>$

θ Vacua

- Must choose a gauge invariant superposition of n-vacua $\Sigma_n e^{i\theta n}|n>$
- Effective coupling $\theta\epsilon_{\mu\nu\rho\sigma}F^{\mu\nu}F^{\rho\sigma}$
- CP violating $E.B$ type term
- Has fermionic zero modes (for free massless fermions)
  - Instanton is a chirality-changing event

Physical Consequences of θ term

- None if there are massless quarks
  - Chiral rotation can set θ_{eff} to zero
- But this raises the strong CP problem
- $\theta_{\text{eff}} = \theta$ - (phase of quark mass matrix)
- Again the relevant thing is a relative phase!
- Neutron electric dipole moment limit
- $\theta_{\text{eff}} < 10^{-12}$
  - Bardeen and Tye

Peccei and Quinn 1977

- Asked ourselves how to get rid of strong CP violation
- Noticed that quarks are massless in the early Universe
- How can θ be irrelevant there but not later?
- Chiral rotation hides it in Yukawa couplings to Higgs
- Is the phase of Higgs vacuum value θ-sensitive?

$\boldsymbol{\theta}$ dependence of Higgs Potential

- Instanton terms in Higgs effective potential
- Integrate out fermions
- Treat instantons as dilute gas (an interaction vertex)
- In standard model get no $\boldsymbol{\theta}$-dependence of Higgs phase
- $\boldsymbol{\Delta V = G e^{i\theta} \phi^{N_f} (\text{up quarks}) \phi^{*N_f} (\text{down quarks})}$
  + hermitian conjugate
- No impact on U(1) symmetry of V
- At the end of the day $\boldsymbol{\theta_{\text{eff}}}$ is arbitrary

Three Ways out

- Keep one quark massless
  - set some Yukawa coupling to zero
- Impose $\theta_{\text{eff}} = 0$ by requiring exact CP
  - spontaneous CP violation to get weak CPV
- Add additional Higgs-type fields and new $U(1)_{PQ}$
  - distinguishes up and down quarks
  - V_{eff} then breaks this U(1) in θ dependent way
  - minimizes at $\theta_{\text{eff}} = 0$

Zero Quark mass

- Current algebra says no for physical up mass
- Could bare up mass be zero?
- Lattice calculations now say no to that as well
- Seems this answer is ruled out

Imposing CP Symmetry

- θ is not just a Lagrangian parameter
- defines QCD vacuum state
- However my prejudice is not a physics argument
- Spontaneous Weak CPV induces small strong CPV
- May be small enough—a multi-loop effect in SM
- Some viable models of this type

$U(1)_{PQ}$

- Not quite a symmetry—broken by θ dependent terms
- Spontaneously broken by Higgs vacuum values
- Hence there is a not-quite Goldstone boson—the axion
- Roberto and I missed this
- Wilczek and Weinberg (separately) pointed it out

Our parenthetical remark

"This same lack of U(1) symmetry was noted by 't Hooft and explains the lack of a Goldstone boson in this theory even though one might naively have expected to find one. In a more physical model it explains the absence of a ninth light pseudoscalar meson."

The axion

- Accelerator experiments do not see such a particle
  - simplest realization of PQ symmetry ruled out
- Certain “invisible axion” theories still viable today
  - devised to avoid accelerator constraints
- Astrophysical constraints—e.g. lifetime of red giant stars
- A possible dark matter particle

Sikivie's Idea to find the axion

- Axion couples to two photons
- If dark matter, then in galactic halo (with roughly known density)
- Cavity with strong magnetic field tuned to resonantly couple to axion

Experiment

- Underway at Livermore Lab—clever refinements!
  - van Bibber, Rosenberg and collaborators
- Already rules out KSVZ axion at expected density
  - Kim, Shifman, Vainshtein and Zakharov
- Factor of 10 to go for DFSZ version (Oct, 2003)
  - Dine, Fischler, Srednicki, and Zhitnitskii