Thoughts about CP Violation

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R. D. Peccei

UCLA

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- Violating CP is not easy
- CP Violation and the Scalar Sector
- SUSY and CP-Violation
- What should we look for?
- Concluding remarks

Violating CP is not easy

- Typically, under CP, operators are replaced by their Hermitian adjoints: e.g.

$W_+^\mu(\mathbf{x}, t) \rightarrow \eta(\mu)\, W_-^\mu(-\mathbf{x}, t)$ [$\eta(0)=-1$; $\eta(i)=1$]

- Schematically, under CP:

$$O(\mathbf{x}, t) \rightarrow O^*(-\mathbf{x}, t)$$

- However, Hermiticity means that a Lagrangian containing the operator O has the structure:

$$L = a\, O + a^*\, O^*$$

where a is a c-number.

- Hence, one sees that, under CP,

  $L \rightarrow L$ only if a= a*

- Thus CP- violation ←→ T- violation

  requires having complex structures in theory.

- However, this per se may not be sufficient

  e.g. 2-generations SM has complex Yukawa couplings, but no physical CP violating phases appear in the theory.

- Furthermore, in some cases, expected CP violation, actually not seen at all (e.g. strong CP problem).

- Noted long ago [Strominger Witten; Dine, Leigh, MacIntire] that in 10-dimensional heterotic string theory, CP can be embedded as discrete subgroup of gauge theory

fermions in E_8 adjoint repr.

CP acts as inversion in 6d compact space

- Thus in these theories CP violating effects arise as result of 10d → 4d compactification and, in principle, one may be able to compute the resulting 4d CP-violating phases from the underlying geometry.[Abel]

- In 4 dimensions, theory involving only fermions and gauge fields is CP-conserving

[g_i ←→ real; A_a^μ ←→ Adjoint], up to θ-terms.

- Topological nature of non-Abelian gauge theory vacuum allow presence of CP-violating θ-terms. However,

$$L_{Weak} = \theta_W \frac{\alpha_2}{8\pi} W_a^{\mu\nu} \tilde{W}^a_{\mu\nu}$$

$\theta_W \to 0$ since SU(2) is chiral theory

$$L_{Strong} = \theta_S \frac{\alpha_3}{8\pi} G_a^{\mu\nu} \tilde{G}^a_{\mu\nu}$$

$\theta_S < 10^{-10}$ since for n edm $< 6.3 \times 10^{-26}$ ecm

- Strong CP problem is still unresolved. Four possibilities bruited about:

i. θ_S just happens to be small [why!!]

ii. u-quark is massless [unlikely?]

iii. There is an extra $U(1)_{PQ}$ symmetry [axions? Sikivie]

iv. CP is spontaneously broken and θ_S calculably small [troubles with low energy CP violation and cosmology?]

- Whatever the reason for $\theta_S < 10^{-10}$ clear that cannot ascribe observed CP-violation, which is connected to flavor-changing transitions, to presence of flavor neutral θ-terms. It must have other origins.

- If there are no elementary scalars, could imagine formation of fermion condensates $<\bar{q}q>\sim e^{id_s}$ or, more likely, $<\bar{T}T>\sim e^{id_{TC}}$ which break CP spontaneously.
- However, difficult to reconcile spontaneous CP breaking with cosmology [Kobzarev Okun Zeldovich].
- Domains of different CP in Universe separated by walls which dissipate slowly as Universe cools.
- Energy density in walls $r \sim s\,T$ exceeds greatly ρ_c if $\sigma \sim v^3$, with $v \sim 250$ GeV

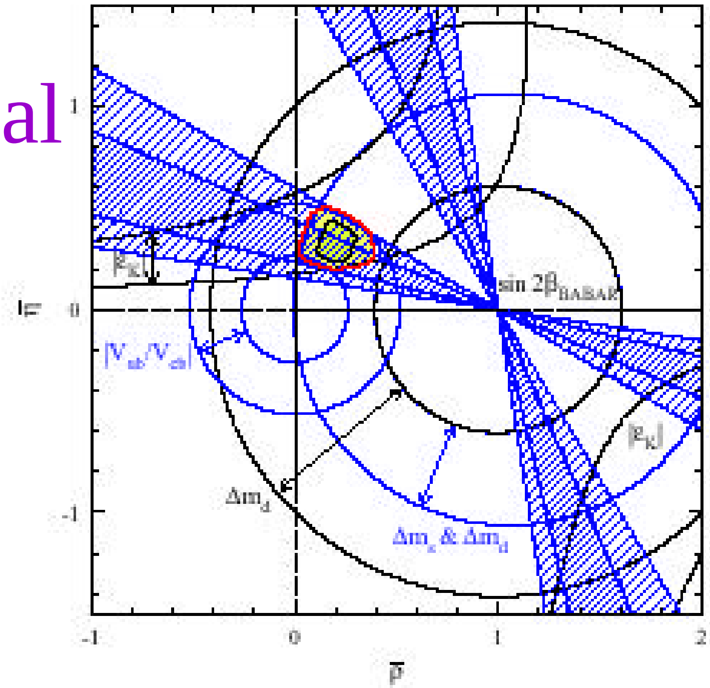
CP Violation and the Scalar Sector

- Because of the above considerations, it is very natural to assume that the experimentally observed CP violation is due to the presence of a scalar sector.
- Indeed, all data both in K and B decays are perfectly consistent with CP violation being due to the CKM paradigm:[Buras]

complex Yukawa couplings $\Rightarrow$ CP violation, if there are 3 or more generations

- It is clearly very important to look for deviations from CKM paradigm, but data and theory do not permit us still to make any such pronouncement.

A. Hocker et al



CKM fit in ρ-η plane

- Look also for CP-violating effects, coming from Higgs sector. However, effects not easy to find!

- SM with one Higgs doublet is very special, since Hermiticity makes all parameters in Higgs potential real:

$$V = m^2 f^* f + l\left(f^* f\right)^2$$

- If there is more than one Higgs doublet, potential in general contains possible CP-violating phases. However, even then there are constraints.
- Illustrate with 2 Higgs doublet example:

$$c = \begin{pmatrix} c^{+} \\ c^{0} \end{pmatrix} \qquad f = \begin{pmatrix} f^{0} \\ f^{-} \end{pmatrix}$$

- Most general potential can be written as sum of terms, reflecting specific symmetries

- To understand structure of V, it is useful to recall that under the weak hypercharge U(1):

$$\chi \rightarrow e^{i\xi/2}\chi \,;\phi \rightarrow e^{-i\,\xi/2}\,\phi$$

- There is a different symmetry, $U(1)_{PQ}$, invoked to set $\theta_S=0$ dynamically. It requires, instead that Higgs fields transform as

$$\chi \rightarrow e^{i\alpha}\chi\,;\;\; \phi \rightarrow e^{i\alpha}\,\phi$$

allowing for a chiral transformation of the quarks.

- Finally, one can consider a discrete symmetry D, invoked to prevent FCNC phenomena, allowing ϕ to couple only to u_R and χ only to d_R :

$$\chi \rightarrow -\chi\,;\,\phi \rightarrow \phi;\, d_R \rightarrow -d_R;\, u_R \rightarrow u_R$$

- The full Higgs potential has 3 pieces:

$$V=V_1+V_2+V_3$$

- The 1st piece V_1 is $SU(2)xU(1)xU(1)_{PQ}xD$ invariant; the 2nd piece V_2 is SU(2)xU(1)xD invariant; while the 3nd piece V_3 is SU(2)xU(1) invariant. One has:

$$V_1 = m_1^2 c*c + m_2^2 f*f + l_1(c*c)^2 + l_2(f*f)^2 + l_3(f*c)(c*f) + l_4(c*c)(f*f)$$

$$V_2 = l_5 e^{id_5}\left(c^T C f\right)^2 + l_5 e^{-id_5}\left(c^T C f\right)^{*2}$$

$$V_3 = m_{12} e^{id_{12}} c^T C f + m_{12} e^{-id_{12}}\left(c^T C f\right)^* + \left[l_6 e^{id_6}\left(c^T C f\right) + l_6 e^{-id_6}\left(c^T C f\right)^*\right](c*c) + \left[l_7 e^{id_7}\left(c^T C f\right) + l_7 e^{-id_7}\left(c^T C f\right)^*\right](f*f)$$

- See that, if one asks that V be just SU(2)xU(1) invariant, the Higgs potential $V= V_1+V_2+V_3$ contains 4 phases: δ_5; δ_{12} ; δ_6 ; δ_7
- However, all of these phases, and associated interactions, are absent if $U(1)_{PQ}$ is a good symmetry.
- If only D is present, one additional Higgs phase δ_5 appears in potential. But, this phase gives no physical effects [Branco Lavoura Silva]
- Phase δ_5 correlated with phase of Higgs VEV θ :

$$<\chi^0>=v_\chi \; ; \; <\phi^0>=v_\phi e^{i\theta}$$

- Minimization of Higgs potential $V=V_1+V_2$ requires that: $\sin(\delta_5+2\theta)=0$.

- Easy to check that all CP-violating phenomena, like e.g. AH^+H^- coupling, are proportional to the phase (δ_5 +2θ):

$$g_{AH+H-} \sim \sin(\delta_5 + 2\theta)$$

- Thus, remarkably, even with 2 Higgs doublets, the requirement that there be no FCNC (i.e. that D be a good symmetry) prevents the appearance of any other CP-violating phases, besides the CKM phase
- There are a number of corollaries to this result. For instance, in invisible axion models, where $U(1)_{PQ}$ is broken at a scale f>>v, no additional low-energy CP-violation ensues in Higgs sector.

- In invisible axion models, the spontaneous breaking of an $U(1)_{PQ}$ invariant potential
  $[\sigma \to e^{-2i\alpha}\sigma;\ \chi \to e^{i\alpha}\chi\ ;\ \phi \to e^{i\alpha}\ \phi]$:

  $$V_{inv.} = \kappa e^{i\delta_a} \sigma^2 \left(\chi^T C \phi\right) + \kappa e^{-i\delta_a} \sigma^{*2} \left(\chi^T C \phi\right)^*$$

  $$with \qquad \kappa < \sigma^2 > = \kappa f^2 \equiv m_a^2 \sim v^2$$

  serves to give an additional complex term beyond V_1 at low energy
- However, also here the phase δ_a, like δ_5 , never gives rise to any physical CP violating effects.
- It is, of course possible, to get Higgs sector CP violating effects, by complicating the theory. The simplest case introduces an additional singlet η

- Keeping D as a good symmetry, but not imposing $U(1)_{PQ}$ (so that $V=V_1+V_2$), it is possible to have a Higgs sector CP violation through the introduction of an extra singlet scalar field η, provided that under D, η→- η.
- Then can add to V a, D-invariant, potential term:

$$V_4=\mu e^{i\delta_4}\eta(\chi^T C\phi) + \mu e^{-i\delta_4}\eta(\chi^T C\phi)^*$$

- If η acquires a VEV, < η>, then out of the 3 phases: δ_4; δ_5;and θ one linear combination gives physical CP-violating effects.
- However, $<\eta> \neq 0$, causes again domain walls to form, so not clear model is sensible cosmologically.

- In general, however, if one introduces a sufficiently complicated Higgs sector eventually it is possible to have some nontrivial CP-violating phases.
- Good example is Weinberg's 3 Higgs doublet model in which there are CP-violating phases associated to the couplings of charged Higgs, $H^{\pm}$, to leptons and quarks.
- Such models can give rise to new observable phenomena, like the transverse μ polarization in $K^+ \rightarrow \pi^0 \mu^+ \nu_\mu$. One finds:

$$\langle P^{\mu}{}_{\perp} \rangle \sim (M^2{}_K / M^2{}_H)[\mathrm{Im}\, g_{H\mu\nu}\, g^*{}_{Hus}]$$

which is an effect not present in CKM model.

SUSY and CP-Violation

- Difficult to take multi-Higgs model seriously, since there is no physical motivation for these theories.
- In this respect, SUSY extensions of the SM have a much better pedigree. CP-violation in these models, however, is largely a function of the assumed SUSY symmetry breaking pattern.
- SUSY SM naturally has 2 Higgs doublets, χ and ϕ, and $V = V_1$, with parameters taking particular values.

- Without SUSY breaking, V also does not break SU(2)xU(1). So need soft SUSY breaking
- In simplest example: SUSY breaking is gravity mediated and is flavor blind. In this case, CP-violating phases appear in:

i. gluino masses: $m_{1/2}\, \lambda_i \lambda_i$

ii. scalar Yukawa int.: $A\Gamma_u \tilde{Q}_L f \tilde{u}_R + A\Gamma_d \tilde{Q}_L c \tilde{d}_R + h.c.$

iii. bilinear scalar terms: $B\mu(\chi^T C \varphi)$ +h.c.

iv. Higgsino mass term: $m\left(\tilde{c}^{\,T} C \tilde{f}\right)$

- Only 2 of these phases are physical. For example, $B\mu \equiv \mu_{12} e^{i\delta_{12}}$, and know this phase is not physical

- Difficulty is not in generating CP-violating interactions, but in keeping the SUSY induced effects below what is presently observed.
- Two types of constraints:

i. Flavor preserving CP violation phenomena, like neutron edm. Typically, [Dugan Grinstein Hall] one finds

$$d_n \sim [300 \left(\frac{100 GeV}{\tilde{m}}\right)^2 \sin \phi_{A,B}]\ \ 6.3 \times 10^{-26}\ ecm$$

where $\tilde{m}$ is a typical spartner mass and $\phi_{A,B}$ are CP-violating phases in the SUSY breaking terms

ii. Flavor violating contributions due to SUSY matter entering in loops. These may, or may not, involve CP violation

•SUSY CP violating effects in the flavor sector depend, in general, on how one assumes the SUSY induced flavor violating effects are controlled [Dine Kramer Nir Shadmi]:

Universality- $\Delta \tilde{m}^2 \ll \tilde{m}^2$

Alignment- $\gamma_{\tilde{g}ij} \sim \delta_{ij}$

Heavy squarks- $\tilde{m} \gg \mathrm{TeV}$

•Only in middle case effects are likely to be measurable, although predictions are rather model dependent e.g. Masiero Piai Ives model with $\delta_{CKM} = 0$ produces ε_K from phase in quark-squark mixing, but then has a resulting small CP asymmetry for $B \to \psi K$

•Because all data is in good agreement with CKM model, at the moment all one has are constraints on squark mass splittings and on mixing angles in the gluino couplings [Abel]

$$\Delta_{ij} = \left(\frac{\tilde{m}_i^2 - \tilde{m}_j^2}{\tilde{m}^2} \right) g_{\tilde{g}\,ij}$$

•Typically, results of a recent analysis [Becirevic et al] give for the B-sector

$$\mathrm{Re}\,\Delta_{13} \approx 2\times 10^{-2}$$

$$\mathrm{Im}\,\Delta_{13} \approx 10^{-2}$$

What should we look for?

- Clearly important to pin down the unitarity triangle, to check the consistency of all flavor-changing CP-violation originating solely from single CKM phase δ_{CKM}
- In the context of the CKM model, measurement of sides of the triangle is as important as measurement of angles.
- In general, however, what is important is to discover evidence for additional CP-violating phases.
- Perhaps most direct signal of CP-violation are Higgs bosons with mixed CP properties.

- Neutral scalars in SUSY models, at tree level have well defined CP: A ←→ 0^- ; h, H ←→ 0^+. This may be vitiated by CP-violating loop effects involving stops and sbottoms, which mix A ←→ h, H [Pilaftsis]
- So can look for CP-violating couplings of Higgs, like:

$$L = \frac{\alpha}{\pi} h \left[a F^{\mu\nu} F_{\mu\nu} + b F^{\mu\nu} \tilde{F}_{\mu\nu} \right]$$

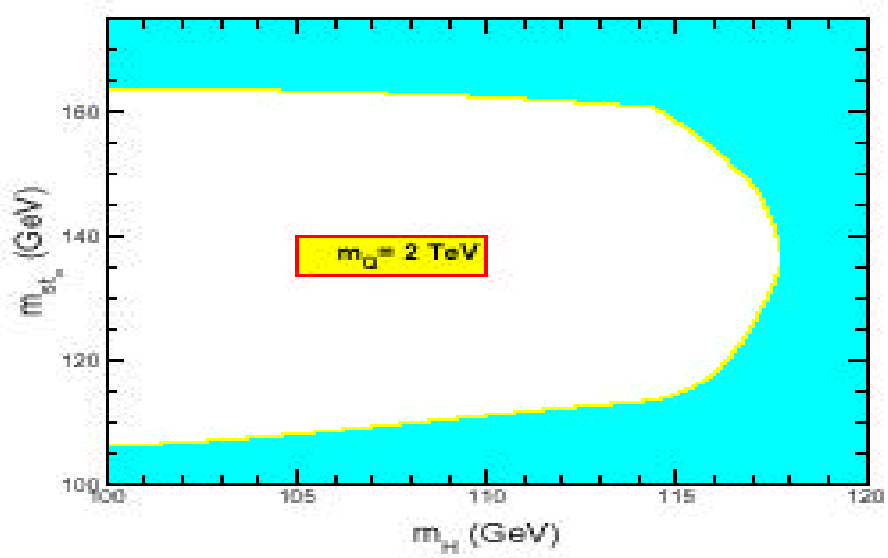
- In practice, difficult to measure CP-odd pieces with much accuracy at LHC. However, NLC is better. Typically one is sensitive to mixing at the level of [Conway et al]:

  LHC: η~b/a ~ 30%; NLC: η~b/a ~ 4%;
- Are there other hints of where to look for?

•We know from the Universe's baryon asymmetry that there are other CP-violating phases, besides δ_{CKM}

•Barely possible that asymmetry is connected to SUSY CP-violating phases at the weak scale. However, parameter space is rather limited:

light stop; m_h at edge of discovery



Quiros

- More likely, and more intriguing, is that the CP phase responsible for the baryon asymmetry is connected to phases in the neutrino sector [Fukugita Yanagida]:
- Out of equilibrium decays of heavy Majorana neutrinos ($M \sim 10^{10}$ GeV) establishes a lepton asymmetry at $T \sim M$. KRS mechanism transmutes this asymmetry into a baryon asymmetry
- Even then, difficult to relate directly the baryon asymmetry CP phase to possible low energy CP violating phenomena in the neutrino sector [Hambye; Hernandez]

- There are two places where, conceivably, can extract information on CP violation in neutrino sector: ν-oscillations; (0ν β β) decay
- Processes are in some sense complementary, and sensitive to different CP-violating phases :

  ν-oscillations ←→ δ^{l}_{CKM}

  (0ν β β) decay ←→ φ_M
- Oscillations can provide direct evidence for CP violation, while double β-decay give more indirect information. In both cases experimental challenges are enormous. [Blondel]

- For oscillation experiments to successfully detect CP-violation θ_{13} must be near Chooz bound [$\sin^2 2\,\theta_{13} < 0.1$] and one has to be able to see differences between ν and $\bar{\nu}$ oscillations:

$$P[\nu_\mu \rightarrow \nu_e] = a + b \sin 2\theta_{13} \sin \delta^{l}_{CKM}$$

$$P[\bar{\nu}_\mu \rightarrow \bar{\nu}_e] = a - b \sin 2\theta_{13} \sin \delta^{l}_{CKM}$$

- For double β-decay, neglecting θ_{13} and assuming a normal hierarchy, [Petcov]

$$M_{ee} = m_e \left| \cos^2\theta_{12} + \sin^2\theta_{12} e^{i\varphi_M} \right|$$

- Theoretical error in M_{ee} makes extraction of φ_M very difficult [Barger et al]

- Unfortunately, neither φ_M nor δ^l_{CKM} are directly related to the CP-phases that control leptogenesis, except for particular circumstances:
- The baryon asymmetry is given by the formula

$$\eta_B = -8/15\,\eta_L = -8/15[\kappa/g^*]\varepsilon$$

Here κ is the washout factor, $g^* \sim 100$ is the number of degrees of freedom and ε is the CP asymmetry in the decay of the heavy neutrino.[Berezhiani]

- In particular ε is connected to neutrino Yukawa coupling h_ν, coupling L_L to N_R, while δ^l_{CKM} and φ_M also depend on the electron Yukawa coupling h_l, coupling L_L to l_R.

Concluding remarks

- Most important task is to get additional experimental information on CP-violation.
- Prospects of this are very good: B factories, dedicated collider B-experiments, $K \rightarrow \pi \upsilon \upsilon$, edm searches, searches for υ CP-violation.
- Very important to understand if simple CKM paradigm explains all CP violation phenomena in the hadronic sector and if there is any signal of CP violation in the leptonic sector.

- On the theoretical side, important to take hints regarding CP violation seriously:

i. CP is conserved in d=10, but broken in d=4.

ii. Even in d=4, difficult to break CP: no strong CP; need scalar sector; no FCNC ⇒ no Higgs phases; must strictly control SUSY breaking.

iii. Phenomena of quite different magnitudes are explained by same large CP-violating CKM phase: $\varepsilon \sim 10^{-3}$; $\varepsilon'/\varepsilon \sim 10^{-3}$; $a_{B \to \psi K_s} \sim 1$.

- Could it be that all CP-violation originates from simple geometrical phase? [Abel]
- My guess: $\delta_0 = \pi / N_{gen}$. Amusing $\delta_{CKM} = (59 \pm 13)^{o}$