On the Origin of CP Violation

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Organization of talk

- Going back $\approx$ "30 years"

  Warning: addition of "time" is not allowed

  Reason: Reference frames have not been specified

- On the Origin of CP violation

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Fermion masses and hierarchy of symmetry breaking

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We suggest that the breaking of a symmetry unifying the families of fermions occurs in stages. We consider the total Lagrangian to be invariant under the group $SU(2)\times U(1)\times G$, where G is a discrete group. The Higgs potential is, however, invariant under $SU(2)\times U(1)\times \tilde{G}$, where $\tilde{G}\supset G$. In a first stage $\tilde{G}$ is broken to a subgroup $H\subset\tilde{G}$, but H is not contained in G. The u and d quarks are naturally massless at the tree level, and we discuss how they could acquire mass through radiative corrections.

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Start with a Lagrangian invariant under

$$SU(3) \times SU(2) \times U(1) \times G$$

$G \to$ discrete family symmetry

Renormalizable Higgs potential invariant under $\tilde{G}$, with

$$\tilde{G} \supset G$$

At a first stage of symmetry breaking $\tilde{G}$ is broken to a subgroup $H \subset \tilde{G}$, but H is not contained in G

Essential in order to avoid Georgi-Pais theorem.

Georgi-Pais theorem:

If a Lagrangian is invariant under a (discrete or continuos) symmetry and if the vacuum expectation values respect this symmetry, at tree level, then the symmetry will still hold in higher orders, provided that at tree level there are no massless scalar meson fields which are not Goldstone bosons.

In the special example of the paper, we considered the tetrahedral group (T) which was also considered by Daniel Wyler.

- The paper is still interesting today (in my opinion), but we have made two "serious" "mistakes":

1) We chose the wrong name for the group. We should have called it A_4 and not the "tetrahedral group".

2) We wrote the paper before "the right time"

Question : How much progress have we made in the last $\gtrsim$ 30 years ?

The "language" has changed ..., a new paradigm ...

"No longer we require renormalizability,
we talk about effective operators,
Froggat-Nielson mechanism ...

Does this necessarily implies "progress" ?

The most important developments:

- ~~Determination~~ Discovery of neutrino masses and leptonic mixing. Open questions:

  U_{e3} and leptonic CP violation

  Dirac or Majorana neutrinos?

- Experimental determination of V^{CKM} and the experimental proof that V^{CKM} is complex!

  This does not imply complex Yukawa couplings!

We do not have yet a theory of Flavour.

– Does this mean that we should "give up", after $\gtrsim$ 30 years?

– No, time is ripe for a great discovery!

LHC is probing the electroweak scale and the generation of masses and mixing of elementary fermions is closely related to the breaking of the electroweak symmetry.

Advise for young people: Try simple solutions!

Example of a simple solution to an important Problem :

GiM !

Even if there is a "family symmetry" behind the observed pattern of fermion masses and mixing, it has been difficult to uncover this symmetry. A possible reason for this: Given the Yukawa couplings Y_u, Y_d one can still make weak-basis transformations:

$$Y_u \to Y_u' = W_L^{\dagger} Y_u W_R^u$$

$$Y_d \to Y_d' = W_L^{\dagger} Y_d W_R^d$$

$\{Y_u, Y_d\}$ and $\{Y_u', Y_d'\}$ contain the same physics

What is the "right basis"?

I do not believe in using the Antropic Principle to solve the Flavour Puzzle.

Various Aspects of CP Violation

- CP Violation in the Quark Sector
  - Discovered for the first time in the Kaon sector
  - Discovered more recently in the B-sector
- CP Violation in the Lepton Sector
  - One expects to have Leptonic CP violation, provided $U_{e3} \neq 0$
- CP Violation needed to create the Baryon Asymmetry of the Universe (BAU)
- Strong CP problem

Can all these manifestations of CP violation have a common origin? **Answer Yes!**

It is likely that having a "common origin" for CP violation requires spontaneous CP violation.

It is non-trivial to construct a realistic model of spontaneous CP violation, since the model should fulfill the following requirements:

(i) The vacuum phase should be able to generate a complex CKM matrix

(ii) One should avoid problems with Higgs mediated Flavour Changing Neutral Currents (FCNC)

Two examples with "Problems"

a) Two Higgs doublet model suggested by T.D.Lee

KM phase is generated but Problems with FCNC, since NFC is not introduced in the Higgs sector

Lee 1973

b) Three Higgs doublet model with Natural Flavour Conservation (NFC) in the Higgs sector. No problem with Higgs mediated FCNC, but CKM real. G.C.B (1980)

We shall concentrate our analysis on extensions of the SM with vector-like isosinglet quarks with charges either $Q = -1/3$ or $Q = 2/3$.

Question : Why study vector-like quarks?

What can they do for us?

Very long list of references ...

In Planck 2011 : R.N. Mohapatra, A. Buras (?), ...
M. Nebot ...

- Vector-like quarks provide a simple, self-consistent framework with naturally small violations of 3x3 unitarity of V^{CKM}

$\Downarrow$

- Lead to naturally small FCNC in the down and/or up quark sector, mediated by Z.
- Provide the simplest framework to have spontaneous CP violation which generates a non-trivial CKM phase with naturally suppressed FCNC.
- Provide a framework where all "manifestations" of CP Violation originate in a single phase of the vev of a complex singlet neutral scalar S

$$\langle S \rangle = V e^{i\theta}$$

A minimal Model

Consider an extension of the SM where the following fields are added to the SM :

- A vectorial quark D^0 : Both D^0_L and D^0_R are $SU(2)_L$ singlets, with charge $Q = -1/3$
- Three right-handed neutrinos ν^0_{Rj}
- A neutral complex singlet S

- Impose CP invariance at the Lagrangian level
- Introduce a Z_4 symmetry on the Lagrangian under which:

$$\psi_\ell^0 \to i\,\psi_\ell^0 \;;\quad e_{R_j}^0 \to i\, e_{R_j}^0 \;;\quad \nu_{R_j}^0 \to i\,\nu_{R_j}^0$$

Lepton doublets

$$D^0 \to -D^0 \;;\quad S \to -S$$

All other fields are invariant under Z_4.

All couplings are real, so CP invariance holds at the Lagrangian level.

The scalar potential contains various terms which do not have phase dependence, but there are terms which have such a dependence

$$V_{phase} = \left(\mu^2 + \lambda_1 S^* S + \lambda_2 \phi^\dagger \phi\right)\left(S^2 + S^{*2}\right) + \lambda_3 \left(S^4 + S^{*4}\right)$$

There is a range of the parameters of the scalar potential, where the minimum is at:

$$\langle \phi^0 \rangle = \frac{v}{\sqrt{2}} \quad ; \quad \langle S \rangle = \frac{V}{\sqrt{2}} e^{i\theta}$$

This minimum violates CP.

Most general $SU(2)\times U(1)\times Z_4$ invariant Yukawa couplings in the quark sector

$$\mathcal{L}_Y = -\left\{ (\overline{u}^\circ \; \overline{d}^\circ)_{L_i} \left[g_{ij}\, \phi\, d^\circ_{R_j} + h_{ij}\, \tilde{\phi}\, u^\circ_{R_j} \right] + \overline{M}\, \overline{D}^\circ_L D^\circ_R + (f_i S + f'_i S^*)\, \overline{D}^\circ_L\, d^\circ_{R_j} \right\} + h.c.$$

$$\underbrace{\text{No } \; \overline{d}^\circ_i\, \phi^\circ\, D^\circ_{R_j}}_{\text{essential to solve the Strong CP problem.}} \text{ couplings} \longrightarrow \text{forbidden by the } Z_4 \text{ symmetry}$$

Quark mass matrix for down-type quarks:

$$\begin{bmatrix} \bar{d}^0_{1L} & \bar{d}^0_{2L} & \bar{d}^0_{3L} & \bar{D}^0_L \end{bmatrix} \left[\begin{array}{ccc|c} & \underset{\text{real}}{m_d} & & 0 \\ \hline M_1 & M_2 & M_3 & \bar{M} \end{array}\right] \begin{bmatrix} d^0_{1R} \\ d^0_{2R} \\ d^0_{3R} \\ D^0_R \end{bmatrix}$$

$$M_j = f_j V e^{i\theta} + f_j' V e^{-i\theta} \qquad ; \qquad \mathcal{U}_L^\dagger \mathcal{M}\mathcal{M}^\dagger \mathcal{U}_L = \begin{bmatrix} d^2 & \\ & D^2 \end{bmatrix}$$

$$\mathcal{U}_L \equiv \begin{bmatrix} K & R \\ S & T \end{bmatrix}$$

may vanish in some models

$$K^{-1} \underbrace{\left[m_d m_d^\dagger - \frac{m_d M^\dagger M m_d^\dagger}{M M^\dagger + \bar{M}^2} \right]}_{m_{\text{eff}}} K = d^2$$

Two terms contributing to m_{eff} are of the same order of magnitude

Yukawa couplings in the Leptonic Sector

Recall that the leptonic fields transform as:

$$\psi_\ell^0 \to i\psi_\ell^0 \quad ; \quad e_R^0 \to i e_R^0 \; ; \; \nu_R^0 \to i\nu_R^0$$

$$\mathcal{L}_\ell = \overline{\psi}_\ell^0 \, G_\ell \, \phi \, e_R^0 + \overline{\psi}_\ell^0 \, G_\nu \, \tilde{\phi} \, \nu_R^0 + \frac{1}{2} \nu_R^{0T} C \left(f_\nu S + f_\nu' S^* \right) \nu_R^0 + \text{h.c}$$

Leptonic mass matrices:

$$\mathcal{M}_\nu = \begin{bmatrix} 0 & m \\ m^T & M \end{bmatrix} \; ; \quad m_\ell = \frac{v}{\sqrt{2}} G_\ell \qquad m = \frac{v}{\sqrt{2}} G_\nu$$

$m \to$ real

$M \to$ complex

$$M = \frac{V}{\sqrt{2}} \left[f_\nu^+ \cos\alpha + i f_\nu^- \sin\alpha \right] \; ; \quad f_\nu^\pm \equiv f_\nu \pm f_\nu'$$

Leptonic Mixing

In the weak-basis where m_ℓ is diagonal, real, the light neutrino masses and the low energy leptonic mixing are obtained from the diagonalization of the effective neutrino mass matrix

$$m_{eff} = - m \frac{1}{M} m^T$$

m is real but since M is a generic complex symmetric matrix, m_{eff} is also a generic complex symmetric matrix, so there is leptonic mixing.

One can also show that one has CP violation needed for Leptogenesis.

Conclusions

- It is possible to construct realistic models where CP is spontaneously broken
- Vector-like quarks may play an important rôle in Flavour Physics, providing:
  - Simple model with Spontaneous CP breaking and a "common source" for all CP violations
  - May provide a "novel approach" to understand the Flavour Puzzle
  - Imply naturally small violations of 3×3 unitarity of V_{CKM} leading to new contributions to:

    $B_d - \overline{B}_d$ mixing, $B_s - \overline{B}_s$ mixing

    β_s can be significantly larger than in the SM.

Happy Birthday, Peter!