Chapter 13

The CKM matrix and the Kobayashi-Maskawa mechanism

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There is a complete draft for the CKM section

Purpose of the section:
Supply the expressions for the CKM and UT parameters

The Unitarity Triangle

The unitarity relations $V_{\mathrm{CKM}} \cdot V^{\dagger}_{\mathrm{CKM}} = 1$ and $V^{\dagger}_{\mathrm{CKM}} \cdot V_{\mathrm{CKM}} = 1$ yield six independent relations corresponding to the off-diagonal zeros in the unit matrix. However, most of these triangles are “squashed”, i.e. they have disparate sides. Only two triangles have sides of comparable length, which means that they are of same order in the Wolfenstein parameter λ. The two relations are

$$V_{\mathrm{ud}}V^*_{\mathrm{ub}} + V_{\mathrm{cd}}V^*_{\mathrm{cb}} + V_{\mathrm{td}}V^*_{\mathrm{tb}} = 0 \qquad (10)$$

$$V_{\mathrm{ud}}V^*_{\mathrm{td}} + V_{\mathrm{us}}V^*_{\mathrm{ts}} + V_{\mathrm{ub}}V^*_{\mathrm{tb}} = 0 \qquad (11)$$

These relations can be depicted by triangles in the complex plane; inserting the Wolfenstein parameterization, both relations turn out to be identical, up to terms of

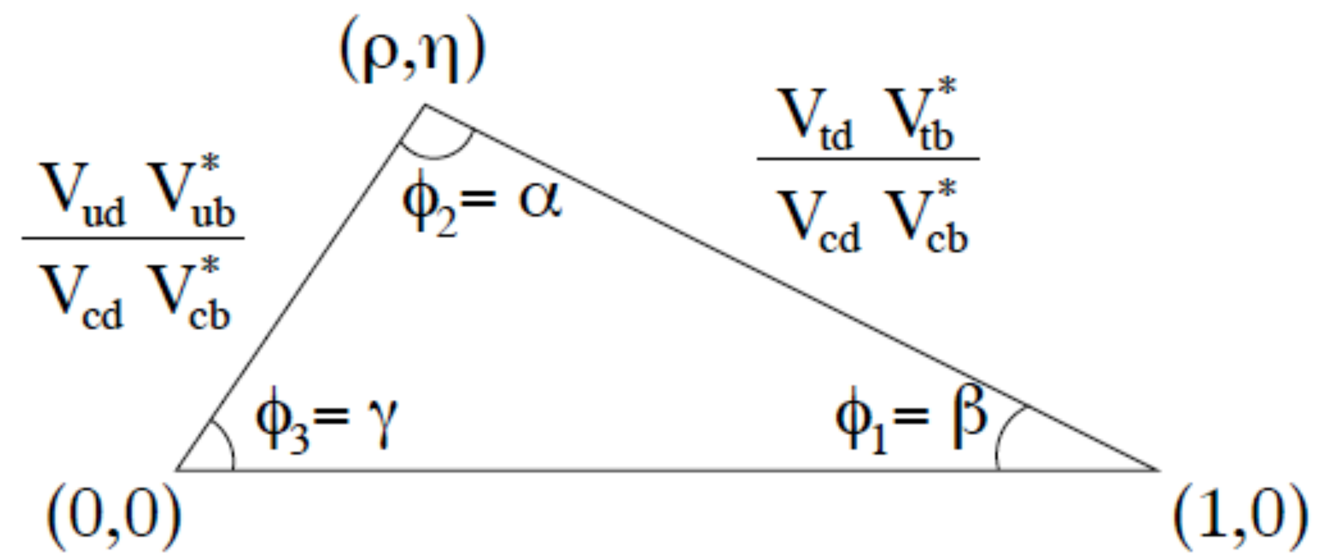

Fig. 1. The Unitarity Triangle.

Conventionally different notations have been used in the literature for the angles of the Unitarity Triangle. In particular the *BABAR* experiment has used α, β, and γ to denote the angles, whereas the Belle experiment has

New since the last meeting:

Subsection on CP violation and Baryogenesis

CP Violation and Baryogenesis

Particle physics experiments of the past thirty years confirmed the standard model even at the quantum level, including also quark mixing and *CP* violation. However, the observed matter-antimatter asymmetry of the universe indicates that there must be additional sources of *CP* violation, since the amount of *CP* violation implied by the CKM mechanism is insufficient to create the observed matter-antimatter asymmetry.

In fact, the abundance of baryons over antibaryons in the universe

$$\Delta = n_{\mathrm{Bar}} - n_{\overline{\mathrm{Bar}}} \qquad (1)$$

is presumably non-zero, but still small compared to the number of photons, the ratio is measured to be $\Delta/n_\gamma \sim 10^{-10}$. Although it is conceivable that there might be regions in the universe consisting of antimatter such as our neighborhood consists of matter, no mechanism is known which could produce from the big bang sufficiently large regions of matter (or antimatter) as we observe it today.

The question under which conditions a non-vanishing Δ can emerge dynamically from the symmetric situation $\Delta = 0$ has been discussed by Sakharov (1967). He identified three ingredients

1. There must be baryon number violating interactions $H_{\mathrm{eff}}(\Delta \neq 0) \neq 0$.
2. There must be *CP* violating interactions. If *CP* were unbroken, then we would have for every process $i \to f$ mediated by $H_{\mathrm{eff}}(\Delta \neq 0)$ the CP conjugate one with the same probability

   $$\Gamma(i \to f) = \Gamma(\bar{i} \to \bar{f})$$

   which would erase any matter-antimatter asymmetry.
3. The universe must have been out of thermal equilibrium. Under the assumption of locality, causality and Lorentz invariance *CPT* is conserved. Since in an equilibrium state time becomes irrelevant on the global scale, *CPT* reduces to *CP*, see 2.

Sakharovs paper remained mainly unnoticed until the first formulation of Grand Unified Theories (GUTs). In these theories it was the first time when all the ingredients were present. In particular, baryon number violation appears naturally since quarks and leptons appear in the same multiplets of the GUT symmetry group. Furthermore, there are additional sources of CP violation, and a phase transition has to take place at the scale M_{GUT}, which has to be quite high to prevent proton decay.

One may also consider electroweak baryogenesis. The electroweak interaction provides CP violation through the CKM mechanism, and the electroweak phase transition has been studied well. Also the first ingredient is present in the electroweak model, since the current corresponding to baryon number is conserved only at the classical level; quantum effects of the electroweak interactions violate baryon number, but still conserve the difference $B-L$ of baryon and lepton number. However, although all ingredients are present, this cannot explain Δ. In particular, the CKM CP violation is to small by several orders of magnitude.

With the evidence of non-vanishing neutrino masses there could be new sources of CP violation in the sector of lepton mixing and the possibility of lepton-number violation. This can generate a leptogenesis, and the surplus of leptons can be transferred to the baryonic sector through $B - L$ conserving interactions.

In any case, additional *CP* violation is needed, beyond the one present in the CKM matrix, in oder to explain the matter-antimatter asymmetry of the universe. The search for this new interactions is one of the main motivation for flavour-physics experiments.

Remaining Tasks

- Include the Buras Parametrization for ρ and η
- (Possibly) a few more sentences explaining the relevance of GIM mechanism
- Go through some polishing and removing of typos
- Add some relevant references
- Include possible other commments from e.g. the discussion at this workshop