HEAVY FLAVOR PHYSICS*

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The quarks c, b and t together with the τ lepton are commonly labeled as heavy flavors. Studies related to these four elementary particles provide an important window to understanding of the least known aspects of the Standard Model of high energy physics as well as vast opportunities for searches of New Physics. This paper contains a pedagogical introduction to the physics of heavy flavors.

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1. Introduction

The Standard Model (SM) [1] of particle physics provides a quantitative description of elementary particles and fundamental interactions (except gravity). In the SM, the elementary building blocks of matter consist of six types of quarks and leptons, grouped in doublets and arranged in three families (generations), as seen in Fig. 1. Equivalently, the flavor quantum number is introduced with a different value for each individual type of quark and lepton. In addition, quarks possess an additional degree of freedom, called the color charge (relevant for strong interactions) which can take one of three values: red, green, and blue. The poetic name "flavor" was coined by Murray Gell-Mann and Harald Fritzsch at a Baskin–Robbins ice-cream store in Pasadena based on the following analogy: "just as ice cream has both color and flavour so do quarks" [2].

The masses of elementary fermions span a wide range of eleven orders of magnitude. The four heaviest ones *i.e.* the three quarks c, b and t together with the τ lepton are called heavy flavors. Studies of their properties play

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a crucial role in elucidating the origin of flavor and mass structure of the Standard Model. Moreover, heavy flavor (HF) physics offers vast possibilities for searches of phenomena which are not described (in particular forbidden) by the SM (Section 4). The latter are commonly labeled as New Physics (NP). Last but not least, HF physics is very closely correlated to **CP** violation (see Section 2) which is crucial in understanding the matter–antimatter asymmetry of the Universe (Section 3).

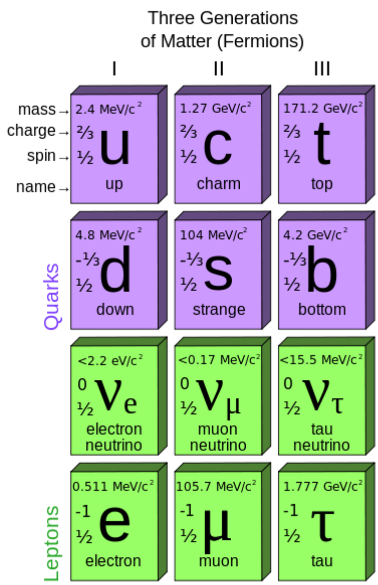

Fig. 1. The elementary building blocks of matter.

2. Discrete symmetries in particle physics

There are three discrete symmetries relevant to particle physics:

- **charge conjugation C** changes the sign of all additive quantum numbers; in the case of the decay of sub-atomic particle this operation corresponds to swapping every particle participating in the process with its antiparticle;
- **parity P** corresponds to the inversion of the 3-dimensional coordinate system; this operation is also called "mirror symmetry" as the inversion of the coordinate axes may be realized in two steps: the first one is a mirror reflection on a coordinate plane, the second is a rotation by an angle 180° with respect to the axis perpendicular to that plane;
- **time reversal T** reverses the orientation of the time coordinate.

According to the **CPT** theorem proved by Lüders and Pauli in 1954, all interactions in nature are unchanged (invariant) on being subjected to the combined operations **C**, **P** and **T**. It is remarkable however, that each of the three discrete symmetries is broken in the weak interaction with the lack of experimental evidence of the **CPT** violation.

3. Baryogenesis

Baryogenesis is a process of generating an excess of baryons over antibaryons, which presumably took place in the early stage of the Universe. This asymmetry resulted in the substantial amount of residual matter that builds the universe today. It is quantitatively parametrized by the ratio of the baryonic number density to the number density of photons in cosmic microwave background radiation: $5.1 \times 10^{-10} < \eta < 6.5 \times 10^{-10}$ [3]. The above estimate is obtained by demanding consistency between the observed abundancies of the light isotopes D, ^{3}He, ^{4}He and ^{7}Li and the predictions of Big-Bang nucleosynthesis. The three minimum conditions necessary for any baryogenesis to occur (regardless of the exact mechanism) were defined by Sakharov in 1967 [4]. These are:

1. baryonic charge nonconservation *i.e.* the presence of at least one process violating the baryon number conservation,
2. asymmetry in particle–antiparticle interactions *i.e.* breaking of **C** and **CP** invariance,
3. depature from thermal equilibrium.

There are several scenarios which fulfill Sakharov's conditions and lead to baryogenesis [5, 6].

4. CP violation in the Standard Model

The flavor and mass structure of the fundamental building blocks of the Standard Model remains one of the biggest enigmas of particle physics to date. The key to this puzzle is the understanding of two distinguished features of weak interactions; these are the breaking of fundamental discrete symmetries discussed above and the ability to change the flavor of elementary particles. Studies of processes involving heavy flavor particles (HF physics) offer unique opportunities to shedding a light on these problems.

It is remarkable that both masses and mixing of flavors of quarks have a common origin in the SM, namely from the Yukawa-type interactions with the Higgs-boson. The respective term in the Standard Model Lagrangian contains two 3×3 complex matrices $Y^{u,d}$. In the process of the spontaneous breaking of the electroweak symmetry, the Higgs field ϕ acquires a non-zero vacuum expectation value $\langle\phi\rangle$. This yields mass terms for the quarks in the form $M^{u,d} = \langle\phi\rangle Y^{u,d}$. The physical states (so-called mass-eigenstates) are obtained by diagonalizing the matrices $M^{u,d}$. The latter is achieved by four unitary matrices $V^{u,d}_{\mathrm{L,R}}$, satisfying the following relations:

$$M^f_{\mathrm{diag}} = \langle\phi\rangle V^f_{\mathrm{L}} Y^f V^{f\dagger}_{\mathrm{R}}\,, \qquad f = u, d\,. \tag{1}$$

Then the Lagrangian describing the charged current $W^\pm$ interactions, written in the base of quark mass-eigenstates, takes the following form

$$\mathcal{L}_{\mathrm{CC}} \propto \left(\overline{u_{\mathrm{L}}}, \overline{c_{\mathrm{L}}}, \overline{t_{\mathrm{L}}}\right) \gamma^\mu W^+_\mu V_{\mathrm{CKM}} \begin{pmatrix} d_{\mathrm{L}} \\ s_{\mathrm{L}} \\ b_{\mathrm{L}} \end{pmatrix} + \mathrm{h.c.} \tag{2}$$

and contains the Cabibbo–Kobayashi–Maskawa (CKM) 3×3 unitary matrix [7] defined as

$$V_{\mathrm{CKM}} \equiv V^u_{\mathrm{L}} V^{d\dagger}_{\mathrm{L}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}. \tag{3}$$

As such, it can be parametrized by three real parameters (quark mixing angles) and a complex phase. The latter is the unique source of **CP**-violating effects in the Standard Model. The magnitudes of elements V_{ik} ($i = u, c, t$; $k = d, s, b$) are direct measures of probabilities of the flavor-changing charged current transition between the quarks k and i. They exhibit a striking hierarchy, shown in Fig. 2, and can be clearly represented in the Wolfenstein parametrization [8]

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(\rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}\left(\lambda^4\right) \tag{4}$$

which depends on four parameters: $A = 0.811^{+0.022}_{-0.012}$, $\lambda = 0.22535 \pm 0.00065$, $\overline{\rho} \equiv \rho(1 - \lambda^2/2) = 0.131^{+0.026}_{-0.013}$ and $\overline{\eta} \equiv \eta(1 - \lambda^2/2) = 0.345^{+0.013}_{-0.014}$ [3].

The unitarity of the CKM matrix leads to a number of relationships among its elements. The six of them which are of the form (column)$^* \times$ (column) $= 0$ (the asterisk denotes here complex conjugation) lead to a sum of three complex numbers equal to zero and can be drawn as a triangle in the complex plane. All the six triangles have the same area which measures the strength of **CP**-violating effects in the Standard Model. Thus the studies of

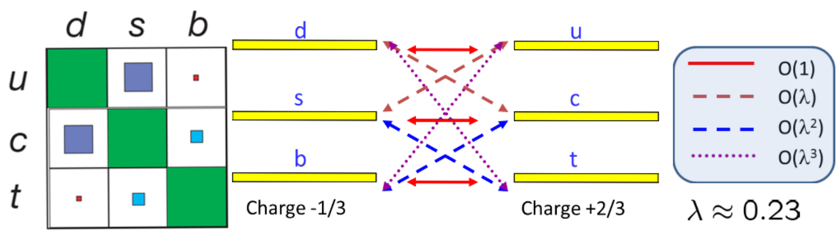

Fig. 2. The hierarchy of elements of the CKM matrix and the respective charged current transitions between quarks.

the violation of **CP** symmetry in the SM can be reduced to the measurements of sides and angles of those triangles. Any inconsistency with the above "triangular" unitarity relations would be a clear sign of New Physics.

The particular triangle corresponding to the above defined product of the first and third column of the CKM matrix

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \tag{5}$$

is often considered the most convenient to study. This is motivated by the fact that the lengths of all three sides of this triangle are of the same order of λ^3. As a result, all three angles are comparable and of large magnitude which is clearly an experimental advantage. Thus the so-called Unitarity Triangle (UT) arises from the relation 5 by normalizing each of its terms by the best-known one (Fig. 3). The above discussion follows the commonly used notation, as given in [3].

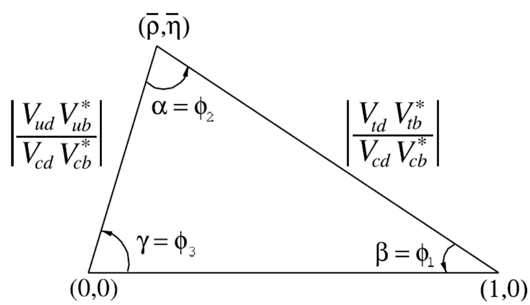

Fig. 3. The overall sketch of the Unitarity Triangle.

Studies of the observables related to the UT yielded recently truly enormous, quantitative and qualitative progress. In particular, the experimental uncertainty of the determination of the apex of the Unitarity Triangle has been improved by two orders of magnitude and the current level of precision of these studies is illustrated in Fig. 4. No striking deviation from the predictions of the SM have been observed so far. However, several observables exhibit discrepancies at the level of 2–4 standard deviations. This fact is generally regarded as the presence of some tension between the observations and the Standard Model. The detailed discussion of these issues can be found in references [10] and [11].

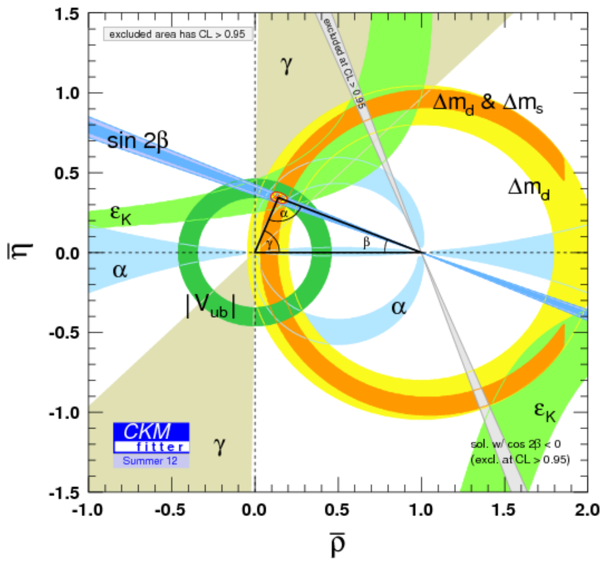

Fig. 4. Constraints in the experimental precision of the apex of the Unitarity Triangle ($\bar{\rho}$–$\bar{\eta}$ plane) [9].

Among the other most prominent achievements in heavy flavor physics over the last two decades are: the first observation of **CP**-violating phenomena in the sector of beauty and charm hadrons, the qualitative improvement in the precision of the measurements of the top quark parameters and a substantial progress in searches for rare decays of beauty and charm hadrons as well as the τ lepton, in particular for those forbidden in the SM. More information about future perspectives of the HF physics can be found in [12–15]. It is worthwhile to underline the full synergy of heavy flavor physics with studies at the so-called energy frontier, performed currently at the Large Hadron Collider (LHC) and the ongoing research of astroparticle physics.

5. Summary

The brief, pedagogical introduction to the heavy flavor physics has been presented. This paper is based on the talk given at the Zakopane Conference on Nuclear Physics on the special session in celebration of the 60th birthday of Marek Jeżabek, Director General of the IFJ PAN.

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