Seach for $B \to \nu\bar{\nu}$ decays at the Belle II experiment

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Abstract

This is a summary.

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Theoretical context

The Standard Model (SM) of particle physics is a theoretical framework that describes the electromagnetic, weak and strong nuclear interactions between elementary particles. Based on the principles of Quantum Field Theory (QFT), it has been tested extensively and has been able to describe the observations of particle physics experiments with great accuracy. However, there are several phenomena that the SM is not able to explain, such as the existence of Dark Matter (DM) or the matter-antimatter asymmetry in the universe. For reasons discussed later on, many tensions with the SM have been previously observed when quark's flavour transitions occur, such as in the $b \to sl^+l^-$, $b \to c\tau\nu$ or $b \to s\nu\bar{\nu}$ transitions. We will study the last one in this thesis, via the prism of the $B \to K\nu\bar{\nu}$ decay. In this chapter, we will first introduce the theoretical framework behind the SM and its limitations (Section 1.1), which will lead us to the formulation of the SM as an Effective Field Theory (EFT) (Section 1.2) and the study of the $B \to K\nu\bar{\nu}$ decay (1.3). We will then mention New Physics (NP) models which could intervene in the $B \to K\nu\bar{\nu}$ decay and the experimental constraints on these models (1.4). Finally, we will present the state of the art in the measurement of the $B \to K\nu\bar{\nu}$ decay (1.5).

1.1 The Standard Model of particle physics

The SM provides mathematical tools to describe the interactions between elementary particles, which can be *fermions*, with half-odd spin, or *bosons*, with integer spin. The elementary bosons, or *gauge bosons*, act as mediators of the fundamental interactions: *electromagnetic*, *weak* and *strong* interactions. The elementary fermions are, in this theory, 12 particles (and 12 anti-particles) forming multiplets of the groups $\mathrm{SU}(3)_C$, $\mathrm{SU}(2)_L$ and $\mathrm{U}(1)_Y$.

The $SU(2)_L \otimes U(1)_Y$ gauge group describes the electroweak interaction, mediated respectively by the $\left(W^i\right)_{i\in[\![1,3]\!]}$ and B bosons, acting on the *weak isospin* T and the *weak hypercharge* Y. At lower energy, this symmetry is spontaneously broken by the Higgs mechanism, leading to the appearance of the $W^{\pm}$ and Z bosons, and the photon γ, which fields are defined as such:

$$W^{\pm} = \frac{1}{\sqrt{2}}\left(W^1 \mp iW^2\right), \quad Z = W^3\cos\theta_W - B\sin\theta_W, \quad A = W^3\sin\theta_W + B\cos\theta_W$$

where θ_W is the weak, or Weinberg, angle. One also need to redefine the generator of $U(1)_Y$ as $Q = T_3 + \frac{Y}{2}$, which is the electric charge operator. Additionnaly, this symmetry breaking mechanism leads to the appearance the Higgs boson H, which is the only scalar elementary particle in the SM.

The $\mathrm{SU}(3)_C$ gauge group describes the strong interaction, and act only on particles with a *colour charge* $C \in \{R, G, B, \bar{R}, \bar{G}, \bar{B}\}$. This group being of dimension 8, it has 8 gauge bosons, called *gluons* $(g_i)_{i\in[\![0,8]\!]}$. Elementary fermions can then be separated in two categories:

- *Quarks*, with a colour charge, which are grouped in three generations, each containing two quarks with electric charge $Q = \frac{2}{3}$ and one with $Q = -\frac{1}{3}$, as follows:

  $$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

  and their anti-particle equivalents. As they interact with the strong nuclear force, quarks are never observed in isolation, but always in bound states called hadrons (except for the top quark because of its mass), since free particles must always have a "null" colour charge. Particles composed of two quarks are called mesons, and those composed of three quarks are called baryons.

- *Leptons*, without a colour charge, which are also grouped in three generations, each containing a charged lepton and a neutrino, as follows:

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$$

and their anti-particle equivalents.

All of the fermions interact weakly, and charged fermions also interact electromagnetically. From the way they act under $SU(2)_L$, one can write the fermions as *weak-isospin doublets*

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L \quad \begin{pmatrix} u' \\ d' \end{pmatrix}_L \quad \begin{pmatrix} c' \\ s' \end{pmatrix}_L \quad \begin{pmatrix} t' \\ b' \end{pmatrix}_L$$

and *weak-isospin singlets*

$$e^-_R \quad \mu^-_R \quad \tau^-_R \quad u'_R \quad c'_R \quad t'_R \quad d'_R \quad s'_R \quad b'_R$$

with the L and R subscripts indicating the chirality of the particles, left-handed or right-handed, respectively. The right-handed neutrinos are not included in the SM.

The primes in the expressions above indicate that the quarks' "*weak*" eigenstates are not the same as their "*mass*" eigenstates. The two bases are related by the unitary Cabibbo-Kobayashi-Maskawa (CKM) matrix, $V_{\text{CKM}} \in M_3(\mathbb{C})$:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \tag{1.1}$$

It is to be noted that one can also right this change of basis for the other quarks' states (u, c, t) and (u', c', t').

This matrix encodes many information. Firstly, due to physical reasons, we need only three mixing angles $(\theta_{12}, \theta_{13}, \theta_{23}) \in \mathbb{R}^3$ and one phase $\delta_{13} \in \mathbb{R}$ in order to fully parametrize this matrix. The phase is interpreted as the *CP-violating* phase and is an important parameter of the SM to measure because of its implication in phenomena such as the *matter-antimatter asymmetry*. Secondly, the squared modulus of the matrix elements are the probabilities for a quark to change flavour.

The unitary of the CKM matrix implies that:

$$\sum_{i\in\{u,c,t\}} V_{ij}V_{ik}^* = \delta_{jk}, \quad (j,k)\in\{d,s,b\}^2 \tag{1.2}$$

$$\sum_{i\in\{d,s,b\}} V_{ji}V_{ki}^* = \delta_{jk}, \quad (j,k)\in\{u,c,t\}^2 \tag{1.3}$$

where δ is the Kronecker symbol.

As one can see from the unitarity and the transitions represented by the matrix elements, change of flavour between same sign quarks, also called Flavour Changing Neutral Current (FCNC), cannot occur at tree level. It is possible at loop level, but the SM predicts very low probabilities for these transitions, because of the Glashow-Iliopoulos-Maiani (GIM) mechanism, which makes them very interesting to study in order to search for NP. An explantion of this mechanism will come in the next section.

Let's go back to Equation (1.2) and develop the expression for $j = b$ and $k = d$:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \tag{1.4}$$

$$\iff 1 + \frac{V_{cd}V_{cb}^*}{V_{ud}V_{ub}^*} + \frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*} = 0 \tag{1.5}$$

supposing that $V_{ud}V_{ub}^* \neq 0$ (which is true for physical reasons). The last relation describe the *unitarity triangle* in the complex plane, with two of its vertices at $C = (0,0)$ and $B = (1,0)$ respectively. The last vertex is defined to be at $A = (\bar{\rho},\bar{\eta}) \in \mathbb{R}^2$ Consequently, the lenghts of the triangle sides are:

$$\bar{AB} = \left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right| \tag{1.6}$$

$$\bar{AC} = \left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right| \tag{1.7}$$

$$\bar{BC} = 1 \tag{1.8}$$

and the angles, also parametrized by the CKM matrix elements, are:

$$\alpha = \arg\left(\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \tag{1.9}$$

$$\beta = \arg\left(\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right) \tag{1.10}$$

$$\gamma = \arg\left(\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right) \tag{1.11}$$

Hence, the measurement of the sides and angles of the unitarity triangle allows to test the SM and search for NP.

1.2 An Effective Field Theory approach to the Standard Model

We now return to the GIM mechanism. Consider a transition from a b quark to a d quark. It is forbidden at tree level but can occur at loop level with the exchange of a W boson. The amplitude of this transition is proportional to the product of the $b \mapsto j$ and $j \mapsto d$ amplitudes and mass of the intermediate quark m_j, where $j \in (u, c, t)$. Moreover because of quantum mechanics, one needs to take the sum of the amplitudes for all possible intermediate quarks.

$$\mathcal{M}_{b \mapsto d} \propto \sum_{j \in (u,c,t)} V_{bj} V_{jd} m_j^2 \tag{1.12}$$

Hence, returning to equation Equation (1.4), if $m_u = m_c = m_t$, we can factorize m_j^2 for $j = u$ in Equation (1.12), and the amplitude of the $b \mapsto d$ transition is null. If such a symmetry of masses exists, FCNC would be forbidden at the one-loop level by the GIM mechanism. However, this equality is viable at very short distance scales and is no longer true at low energies, meaning that the GIM mechanism breaks down at the one-loop level.

This is a good example of the limitations of the SM. The breakdown of the model as a function of the energy scale indicates that SM is an effective theory, meaning that it is a low-energy approximation of a more fundamental theory. Studying B meson physics implies that it is necessary to work at various energy scales: the energy scale for new physics, denoted Λ_{NP}; the electroweak scale at M_W, the mass of the W boson; the scale of the b quark m_b; and the energy scale of the strong interaction, Λ_{QCD}. The usual approach to the SM is to write Hamiltonian as sum of operators, respecting symmetries of the SM, times a coefficient. Thus, we can write an effective Hamiltonian at any energy scale $\mu \in \mathbb{R}_{>0}$ as:

$$\mathcal{H}_{\text{eff}} = \sum_{i=1}^{N} C_i(\mu) O_i(\mu) \tag{1.13}$$

where $N \in \mathbb{N}^*$ is the order of the series expansion, O_i are operators and C_i are the *Wilson* *coefficients*, which describe the short-distance physics at higher energy scale. For a weak decay, the effective Hamiltonian can be written as:

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \sum_{i=1}^{N} V^i_{\text{CKM}} C_i(\mu) O_i(\mu) + h.c. \tag{1.14}$$

where G_F is the *Fermi constant*, V^i_{CKM} are elements of the CKM matrix and *h.c.* stands for *hermitian conjugate*.

1.3 The $B \to K\nu\bar{\nu}$ decay in the Standard Model

Let's develop Equation (1.14) for the $b \to sll$ decay, where l can be any lepton, for $\mu \approx m_b$:

$$\begin{aligned}\mathcal{H}_{\text{eff}} \approx -\frac{G_F}{\sqrt{2}} V^*_{ts} V_{tb} \Bigg[\sum_{i=1}^{6} C_i(\mu) O_i(\mu) + C_{7\gamma}(\mu) O_{7\gamma}(\mu) + C_{8G}(\mu) O_{8G}(\mu) + C_{9V}(\mu) O_{9V}(\mu) + C_{10A}(\mu) O_{10A}(\mu) \\ + C^{\nu}_L(\mu) O^{\nu}_L(\mu) + C^{\mu}_L(\mu) O^{\mu}_L(\mu) \Big] + h.c.\end{aligned} \tag{1.15}$$

The effective hamiltonian here is only an approximation since we neglected the $V^*_{us} V_{ub}$ term, as $V^*_{ts} V_{tb}$ is greater than $V^*_{us} V_{ub}$ by a factor 50. The operators O_i are defined as:

$$O_1 = (\bar{s}_i) \tag{1.16}$$

1.4 New Physics models in the $B \to K\nu\bar{\nu}$ decay

1.5 State of the art

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Conclusion

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List of acronyms

CKM Cabibbo-Kobayashi-Maskawa. 7, 8, 10

DM Dark Matter. 5

EFT Effective Field Theory. 5

FCNC Flavour Changing Neutral Current. 8, 9

GIM Glashow-Iliopoulos-Maiani. 8, 9

NP New Physics. 5, 8, 9

QFT Quantum Field Theory. 5

SM Standard Model. 5, 6, 7, 8, 9

Bibliography

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