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

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Abstract

This is a summary.

Contents

1

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 weak eigenstates are not the same as the mass eigenstates. The two bases are related by the unitary Cabibbo-Kobayashi-Maskawa (CKM) matrix, $V_{\mathrm{CKM}} \in M_3(\mathbb{R})$:

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

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. This is called the *standard* representation of the CKM matrix. Another useful representation, related to the standard one, is called the *Wolfenstein* representation, which uses the four parameters $(\lambda, A, \rho, \eta) \in \mathbb{R}^4$.

The unitary of the CKM matrix implies that:

$$\sum_{i \in \{u,c,t\}} V_{ij} V^*_{ik} = \sum_{i \in \{u,c,t\}} V_{ji} V^*_{ki} = \delta_{jk} \tag{1.2}$$

where δ is the Kronecker symbol and $(j, k) \in \{d, s, b\}^2$. Developping the first sum of Equation (1.2) for $j = d$ and $k = b$ gives:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \tag{1.3}$$

$$\iff 1 + \frac{V_{cd}V_{cb}^*}{V_{ud}V_{ub}^*} + \frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*} = 0 \tag{1.4}$$

supposing that $V_{ud}V_{ub}^* \neq 0$ (which is true for physical reasons). The last relation describe a *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 $A = (\bar{\rho}, \bar{\eta})$, with

$$\bar{\rho} = \rho\left(1 - \frac{\lambda^2}{2}\right), \quad \bar{\eta} = \eta\left(1 - \frac{\lambda^2}{2}\right) \tag{1.5}$$

using the Wolfenstein parameters. Consequently, the lenghts of the triangle sides are:

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

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

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

1.2 An Effective Field Theory approach to the Standard Model

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

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

DM Dark Matter. 5

EFT Effective Field Theory. 5

NP New Physics. 5

QFT Quantum Field Theory. 5

SM Standard Model. 5, 6, 7

Bibliography

[1] A N Kolmogorov. *Foundations of the theory of probability.* Chelsea Publishing Company, New York, NY, USA, 1956. (cited on page 8)