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Nuclear Physics B (Proc. Suppl.) 234 (2013) 173–176

NUCLEAR PHYSICS B PROCEEDINGS SUPPLEMENTS

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Future prospects for the determination of the Wilson coefficient $C'_{7\gamma}$

Andrey Tayduganov[a,b]

[a]Laboratoire de Physique Théorique, CNRS/Université Paris-Sud 11 (UMR 8627)
91405 Orsay, France
[b]Laboratoire de l'Accélérateur Linéaire, Université Paris-Sud 11, CNRS/IN2P3 (UMR 8607)
91405 Orsay, France

Abstract

We discuss the possibilities of assessing a non-zero $C'_{7\gamma}$ from the direct and the indirect measurements of the photon polarization in the exclusive $b \to s\gamma^{(*)}$ decays. We focus on three methods and explore the following three decay modes: $B \to K^*(\to K_S\pi^0)\gamma$, $B \to K_1(\to K\pi\pi)\gamma$, and $B \to K^*(\to K\pi)\ell^+\ell^-$. By studying different New Physics scenarios we show that the future measurement of conveniently defined observables in these decays could provide us with the full determination of $C_{7\gamma}$ and $C'_{7\gamma}$.

Keywords: Rare Decays, Beyond Standard Model, *B*-Physics

1. Introduction

The radiative decay $b \to s\gamma$ has been extensively studied as a probe of the flavour structure of the Standard Model (SM) as well as New Physics (NP), beyond the SM. While the majority of studies has been focused on the prediction of the decay rates of exclusive and inclusive $b \to s\gamma$ decays, relatively few studies of the right-handed currents in these decays have been made. In the SM, the emitted photon is predominantly left-handed in b, and right-handed in $\bar{b}$ decays. This is due to the fact that the dominant contribution comes from the chiral-odd dipole operator $O^{(\prime)}_{7\gamma} = \frac{e}{16\pi^2} m_b \bar{s}_{L(R)}\sigma_{\mu\nu} b_{R(L)}$. As only left-handed quarks participate in weak interaction, this effective operator induces a helicity flip on one of the external quark lines, which results in a factor m_b for $b_R \to s_L\gamma_L$, and a factor m_s for $b_L \to s_R\gamma_R$. Hence, the emission of right-handed photons is suppressed by a factor m_s/m_b. This suppression can be lifted in some NP models where the helicity flip occurs on an internal line, which brings in a factor $m_{\rm NP}/m_b$ instead of m_s/m_b.

If the amplitude for $b \to s\gamma_R$ is of the same order as the SM prediction, or the enhancement of $b \to s\gamma_R$ goes along with the suppression of $b \to s\gamma_L$, the impact on the branching ratio is small since the two helicity amplitudes add incoherently. This implies that there can be a substantial contribution of NP to $b \to s\gamma$ escaping detection when only branching ratios are measured. Therefore, the photon polarization measurement could provide a good test of the SM or at least a useful indication of NP.

2. Various methods for determination of $C'_{7\gamma}$

The $b \to s\gamma$ process can be described by the effective Hamiltonian[1],

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V^*_{ts}\left[C_{7\gamma}(\mu_b)O_{7\gamma}(\mu_b) + C'_{7\gamma}(\mu_b)O'_{7\gamma}(\mu_b)\right], \tag{1}$$

where the short-distance Wilson coefficient $C_{7\gamma}(C'_{7\gamma})$ describes the left(right)-handed photon emission amplitude of $b \to s\gamma$. In the SM, $C'_{7\gamma}/C_{7\gamma} \simeq m_s/m_b \simeq 0.02$.

Three methods have been proposed for the measurement of the photon polarization or equivalently the ratio $C'_{7\gamma}/C_{7\gamma}$:

[1]The short-distance QCD effects induce the mixing of $O^{(\prime)}_{7\gamma}$ with the other operators which we omitted writing in Eq. (1). This effect can be absorbed by defining the so-called "effective" coefficients $C^{(\prime)\,\rm eff}_{7\gamma}$. For notational simplicity, whenever $C^{(\prime)}_{7\gamma}$ appears in what follows, $C^{(\prime)\,\rm eff}_{7\gamma}$, evaluated at the scale $\mu_b \simeq m_{b,\,\rm pole} = 4.8$ GeV, will be understood.

Email address: `Andrey.Tayduganov@th.u-psud.fr` (Andrey Tayduganov)

0920-5632/$ – see front matter
doi:10.1016/j.nuclphysbps.2012.12.008

- An *indirect* determination of the photon polarization, proposed by Atwood *et al.* [1], is the measurement of the time-dependent mixing-induced CP-asymmetry in the radiative neutral B-mesons decays such as $B \to K^*(\to K_S\pi^0)\gamma$, and $B_s \to \phi\gamma$, which is determined by the S parameter,

$$S \simeq \frac{2\mathcal{I}m[e^{-i\phi_M}\, C_{7\gamma}C'_{7\gamma}|}{|C_{7\gamma}|^2 + |C'_{7\gamma}|^2}\,, \tag{2}$$

  where ϕ_M is the phase in the $B-\overline{B}$ mixing, which in the SM is $\phi_d = 2\beta \simeq 43°$, and $\phi_s \simeq 0$, for the B_d and B_s mixing, respectively. Such measurements are expected to be made at future super B factories, reduce the experimental error on the asymmetry parameter $S_{K^*\gamma}$ down to 2%.

- A *direct* determination, proposed by Gronau *et al.* [2], is based on the study of the angular distribution of the three-body final state, $K\pi\pi$, coming from the axial vector $K_1(1^+)$-meson decay, in $B \to K_1(\to K\pi\pi)\gamma$, and extraction of the polarization parameter λ_γ,

$$\lambda_\gamma \simeq \frac{|C'_{7\gamma}|^2 - |C_{7\gamma}|^2}{|C'_{7\gamma}|^2 + |C_{7\gamma}|^2}\,. \tag{3}$$

  In Ref. [3] this method was improved by using a new variable ω, which includes not only the angular dependence but also the dependence on the three-body Dalitz variables which can significantly improve the sensitivity of the measurement of the polarization parameter. Recently measured by the Belle collaboration $\mathcal{B}(B \to K_1(1270)\gamma)$ appeared to be comparable to $\mathcal{B}(B \to K^*\gamma)$, which opened the possibility of measuring the photon polarization in $B \to K_1\gamma$.

- Another *indirect* way to study the right-handed currents is based on the angular analysis in the semileptonic $B \to K^*(\to K\pi)\ell^+\ell^-$ decay[2]. In particular, two transverse asymmetries, $\mathcal{A}_T^{(2)}(q^2)$ and $\mathcal{A}_T^{(\mathrm{im})}(q^2)$, introduced in Refs. [5, 6], are highly sensitive to the $b \to s\gamma$ process at very low dilepton invariant mass squared $q^2 = (p_{\ell^+} + p_{\ell^-})^2$,

$$\begin{aligned}\lim_{q^2\to 0}\mathcal{A}_T^{(2)}(q^2) &= \frac{2\mathcal{R}e[C_{7\gamma}C'^*_{7\gamma}]}{|C_{7\gamma}|^2 + |C'_{7\gamma}|^2}\,,\\ \lim_{q^2\to 0}\mathcal{A}_T^{(\mathrm{im})}(q^2) &= \frac{2\mathcal{I}m[C_{7\gamma}C'^*_{7\gamma}]}{|C_{7\gamma}|^2 + |C'_{7\gamma}|^2}\,.\end{aligned} \tag{4}$$

[2] In our analysis we do not consider the pollution by the $B \to K_0^*(\to K\pi)\ell^+\ell^-$ events [4].

These three methods, having their own advantages and disadvantages, can be complementary to each other. Combination of all three of them can in principle put a strong constraint on the short-distance $C^{(\prime)}_{7\gamma}$ coefficients in a model-independent way which then can be used as a constraint in building the NP models.

3. Constraints on $C'_{7\gamma}$ combining various methods of the photon polarization determination

3.1. Current constraint on $C'_{7\gamma}$ by $\mathcal{B}(B \to X_s\gamma)$ and $S_{K^*\gamma}$

In Fig. 1 we show the constraints on $C'_{7\gamma}/C_{7\gamma}$ available at present and compare them with those that are planned to be obtained from the future measurements. For illustration, we consider two NP scenarios[3]:

- scenario *I*: $C^{(\mathrm{NP})}_{7\gamma} \in \mathbb{R}$, $C'^{(\mathrm{NP})}_{7\gamma} \in \mathbb{R}$;
- scenario *II*: $C^{(\mathrm{NP})}_{7\gamma} = 0$, $C'^{(\mathrm{NP})}_{7\gamma} \in \mathbb{C}$;

In all plots presented in Figs. 1–3, we use the constraint from the inclusive rate. The region outside the gray (dark gray) circle is excluded at 3σ (1σ) level by the current measurement [8],

$$\mathcal{B}^{\exp}(B \to X_s\gamma) = (3.55 \pm 0.24) \times 10^{-4}\,, \tag{5}$$

which we combined with the SM prediction given in Ref. [9].

In Fig. 1 we show the constraints from already measured $\mathcal{B}(B \to X_s\gamma)$ and $S_{K^*\gamma}$. Orange (dark orange) region represents the $\pm 3\sigma$ ($\pm 1\sigma$) region allowed by the current measurement of $S_{K^*\gamma}$ [8],

$$S^{\exp}_{K^*\gamma} = -0.16 \pm 0.22\,. \tag{6}$$

Performing a χ^2-fit of $\mathcal{B}(B \to X_s\gamma)$ and $S_{K^*\gamma}$, we obtain the 95% and 68% CL regions for $C'_{7\gamma}$ for each considered NP scenario. One can see from the plots in Fig. 1, that there is still room for NP. Note, however, the apparent ambiguities in the $C_{7\gamma} - C'_{7\gamma}$ plane: in scenario *I* it is fourfold in the $C_{7\gamma} - C'_{\gamma}$ plane and twofold in the $\mathcal{R}e[C'_{7\gamma}] - \mathcal{I}m[C'_{7\gamma}]$ plane in scenario *II*, respectively. Therefore, it is clear that additional observables are required to pin down the real and imaginary parts of $C^{(\prime)}_{7\gamma}$.

[3] For more tested scenarios and details see Ref. [7]