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Probing photon helicity in radiative B decays via charmonium resonance interference

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Abstract

We investigate a new method to probe the helicity of the photon emitted in the $b \to s\gamma$ transition. The method relies on the observation of interference effects between two resonance contributions, $B \to K^*(K\gamma)\gamma$ and $B \to \eta_c(\gamma\gamma)K$ or $B \to \chi_{c0}(\gamma\gamma)K$ to the same final state $K\gamma\gamma$. Decays of the type $B \to K_{\mathrm{res}}(K\gamma)\gamma$ dominate the $B \to K\gamma\gamma$ yield throughout most of the phase space, and may be accessible at current B meson facilities already.

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1. Introduction

Flavor-changing neutral currents are an important testing ground for the Standard Model (SM) of elementary particles. The quark transition $b \to s\gamma$ has played an outstanding role in this respect by providing direct experimental evidence for the penguin diagram process, which is expected to be particularly sensitive to contributions from physics beyond the SM. Recent measurements of the $b \to s\gamma$ rate [1], however, agree very well with theoretical predictions [2], leaving little hope for observing hints of new physics via the decay rate only. Consequently, recent efforts have focused on finding additional observable degrees of freedom related to $b \to s\gamma$, such as CP asymmetries or the helicity of the emitted photon, in order to subject the SM to ever more stringent tests. In a similar vein, the decay $B \to X_s\gamma\gamma$ and its exclusive manifestation $B \to K\gamma\gamma$ have been studied in this context [3–5]. In analogy to $b \to sl^+l^-$, the diphoton invariant mass spectrum and forward–backward asymmetries have been suggested as probes for new physics beyond the SM [6].

In this Letter, we point out the significance of contributions to the $K\gamma\gamma$ final state that occur via radiatively decaying kaon resonances: $B \to K_{\mathrm{res}}\gamma$, with K_{res} being any kaon resonance, such as $K^*(892)$ or higher, that can decay to $K\gamma$. We will further show how these decays may be used to extract information on the helicity of the emitted photon in the $b \to s\gamma$ amplitude at future high-statistics B-meson facilities.

It was first noted by Atwood, Gronau, and Soni [7] that the photon helicity in $b \to s\gamma$ carries information on the underlying interaction. While the SM amplitude for $b \to s\gamma$ results in a predominantly left-handed photon (right-handed for $\bar{b} \to \bar{s}\gamma$), there are extensions of the SM that could alter the helicity of the photon without affecting much the rate of the decay. Thus several methods for an indirect determination of the photon helicity in radiative B decays have been devised: (1) study of the *interference between* $b \to s\gamma$ *and* $\bar{b} \to \bar{s}\gamma$, made possible by the phenomenon of B^0–$\bar{B}^0$ mixing [7]; (2) analysis of the *decay photon by means of its conversion to* e^+e^- [8] (see also [9] for the case of off-shell photons); (3) analysis of the *recoil system arising from the hadronization of the* s*-quark* in $b \to s\gamma$ [10]; (4) use of a *polarized initial state*, i.e., b-baryon decay,

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to infer the photon polarization from angular correlations with the final state [11,12]. Yet another way to analyze the decay photon is provided by the interference with another photon in a well-known state arising from the *same decay*. For example, $B \to K^*(K\gamma)\gamma$ can interfere with $B \to Kc\bar{c}(\gamma\gamma)$, where $c\bar{c}$ is a charmonium state such as η_c or χ_{c0}.

Photon pairs arising from η_c ($J^P = 0^-$) decay are known to be in an exact state of perpendicular polarization [13], i.e., a state with photon spin orientation given by $\mathbf{k}_1 \cdot [\boldsymbol{\epsilon}_1(\mathbf{k}_1) \times \boldsymbol{\epsilon}_2(\mathbf{k}_2)]$, where $\boldsymbol{\epsilon}_1$ and $\boldsymbol{\epsilon}_2$ ($\mathbf{k}_1$ and $\mathbf{k}_2$) are the transverse polarization (momentum) vectors of the two photons. Similarly, photons from χ_{c0} ($J^P = 0^+$) decay are in a state of parallel polarization ($\boldsymbol{\epsilon}_1 \cdot \boldsymbol{\epsilon}_2$). Thus we may use η_c and χ_{c0} as probes to analyze the polarization state of the photons from $B \to K^*(K\gamma)\gamma$, since photons from η_c (χ_{c0}) will only interfere with the perpendicular (parallel) polarization component.

2. $B \to K^*(K\gamma)\gamma$ amplitude

The SM amplitude for $B \to K^*(K\gamma)\gamma$ as given in Ref. [4] is based on a description of $b \to s\gamma$ in the framework of a leading-order effective Hamiltonian,

$$\mathcal{H}_{\mathrm{eff}} = -4\frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* C_7 O_7, \qquad (1)$$

with G_F the Fermi constant, C_7 the Wilson coefficient of the local operator $O_7 = (em_b)/(16\pi^2)\bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$, e the electric charge, m_b the mass of the b-quark, $F^{\mu\nu}$ the electromagnetic field tensor and $\sigma_{\mu\nu} = \frac{i}{2}(\gamma_\mu\gamma_\nu - \gamma_\nu\gamma_\mu)$. V_{tb} and V_{ts} are the usual Cabibbo–Kobayashi–Maskawa matrix elements. The full amplitude is then given as $\mathcal{M}_{K^*} = [T^{\mu\nu}(k_1,k_2) + T^{\nu\mu}(k_2,k_1)]\epsilon_\mu^*(k_1)\epsilon_\nu^*(k_2)$ with

$$\begin{aligned} T^{\mu\nu}(k_1,k_2) = {} & \frac{em_b g F}{16\pi^2} \\ & \times 4\frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* C_7 \epsilon^{\alpha\nu\gamma\delta} k_{2\alpha}(p_B - k_1)_\gamma k_{1\beta'} \\ & \times \frac{g_{\delta\sigma'} - \frac{(p_B-k_1)_\delta (p_B-k_1)_{\sigma'}}{m_{K^*}^2}}{(p_B-k_1)^2 - m_{K^*}^2 + i m_{K^*}\Gamma_{K^*}} \\ & \times \big[i\epsilon^{\mu\beta'\sigma'\tau'}(p_B-k_1)_{\tau'} \\ & - \big(g^{\mu\sigma'}(p_B-k_1)^{\beta'} - g^{\beta'\sigma'}(p_B-k_1)^{\mu}\big)\big], \qquad (2) \end{aligned}$$

where k_i are the 4-vectors $(E, \mathbf{p})$ of the photons, and p_B, p_K the 4-vectors of the B and K mesons. The constants g and F are related to the coupling strengths for $K^* \to K\gamma$ and $B \to K^*\gamma$, respectively, and are different for neutral (B^0) and charged decays (B^+).

The decay distribution in the plane of the two photon energies (Dalitz plot) is shown in Fig. 1. It exhibits the typical $(1 + \cos^2\theta)$ shape along the resonance lines, as expected for the decay of a pseudoscalar particle into a pseudoscalar and two vectors via an intermediate vector resonance state. It also features a non-negligible fraction of decays in the central region of the Dalitz plot, outside the two resonance lines. This region is populated by decays receiving contributions from *both* amplitudes, $B \to K^*\gamma \to (K\gamma')\gamma$ and $B \to K^*\gamma' \to (K\gamma)\gamma'$. Despite the suppression from the Breit–Wigner resonance shape the effect of this interference amplitude results in a substantial enhancement of the over-all branching fraction of the decay. Indeed, from the distribution of events we find that $\mathcal{B}(B \to K^*(K\gamma)\gamma) \approx 3.85\mathcal{B}(B \to K^*\gamma)\mathcal{B}(K^* \to K\gamma)$. Combining this estimate with recent experimental data on $B \to K^*\gamma$ [14] and $K^* \to K\gamma$ [15] we obtain branching fractions of (3.54 ± 0.35) for B^0 and (1.54 ± 0.15) for B^+ in units of 10^{-7}, well accessible with the next generation of B factories [16] and perhaps also at hadron colliders [17] if backgrounds can be controlled.

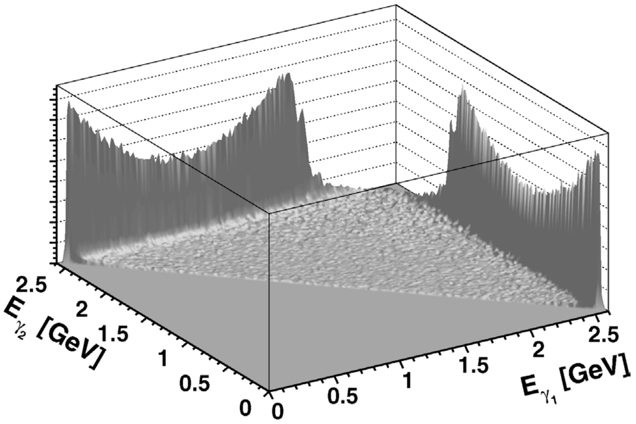

Fig. 1. Decay distribution for $B \to K^*\gamma \to K\gamma\gamma$ in the plane of the two photon energies (Dalitz plot).

3. Other contributions to $B \to K\gamma\gamma$

Other transitions yielding the $K\gamma\gamma$ final state include a non-resonant (short-distance) contribution, $b \to s\gamma$ contributions via higher kaon resonances decaying to $K\gamma$, contributions from $\eta(\gamma\gamma)K$ and $\eta'(\gamma\gamma)K$, as well as the analog contributions from charmonium resonances (η_c and χ_c states).

The non-resonant contribution is negligible with respect to the K^* contribution everywhere in phase space. Our evaluation of the amplitude given in [4] confirms the small non-resonant branching fraction of order 10^{-9} first reported by Hiller and Safir [5] in contradiction to the value given in [4]. Choudhury et al. have recently acknowledged a numerical error in their computations and published updated values [18] in accordance with [5].

The contributions from higher kaon resonances decaying to $K\gamma$ are difficult to assess with current experimental information. Recent measurements of $B \to K_1(1270)\gamma$ and $K_2^*(1430)\gamma$ [19] and corresponding radiative width determinations for these resonances [20] indicate that the effective $K\gamma\gamma$ branching fractions from these higher resonances are in the same range as for $K^*(892)$. Since a number of other kaon resonances may contribute to this final state, the overall $B \to K\gamma\gamma$ branching fraction due to kaon resonances could be an order of magnitude larger than our estimate for K^* only, bringing it to a level that may be accessible at currently running B factories. In view of the coarse experimental information available we leave these contributions to future investigations and assume here that