Probing New Physics with $b \to s\gamma$ decays

Dan Pirjol
Department of Physics, UCSD
9500 Gilman Drive
La Jolla, CA 92093

Abstract

In the Standard Model, the photon emitted in $b \to s\gamma$ decays is predicted to be left-handed polarized. We discuss the types of New Physics which can produce a deviation from this prediction, focusing on the Minimal Supersymmetric Standard Model. A new method is proposed for testing these predictions, which makes use of angular correlations in exclusive $B \to K^{**}(\to K\pi\pi)\gamma$ decays.

Rare radiative $b \to s\gamma$ decays have been extensively investigated both as a probe of the flavor structure of the Standard Model and for their sensitivity to any new physics beyond the SM. The present experimental average of the $B \to X_s\gamma$ inclusive rate $Br(B \to X_s\gamma) = (3.22 \pm 0.40) \times 10^{-4}$ [1] agrees well with the Standard Model prediction, to next-to-leading order in perturbation theory $Br(B \to X_s\gamma) = (3.54 \pm 0.49) \times 10^{-4}$ (corresponding to a pole mass ratio $m_c/m_b = 0.25 \pm 0.06$) [2]. In addition to the rather well predicted inclusive branching ratio, there is a unique feature of this process within the SM which drew only moderate theoretical attention and which has not yet been tested. Namely, the emitted photons are left-handed in radiative B^- and $\overline{B}^0$ decays and are right-handed in B^+ and B^0 decays. In the SM the photon in $b \to s\gamma$ is predominantly left-handed, since only left chiral quarks couple to the W into loops.

This prediction holds in the SM to within a few percent, up to corrections of order Λ/m_b, for exclusive and inclusive decays. On the other hand, in certain extensions of the Standard Model, an appreciable right-handed component can be induced in $b \to s\gamma$ decays. While measurements of the inclusive radiative decay rate agree with SM calculations, no evidence exists so far for the helicity of the photons in these decays.

In view of its popularity as a model of New Physics, we will focus the discussion below on the Minimal Supersymmetric Standard Model (MSSM) [3] (an alternative source of nonstandard photon helicity is the left-right symmetric model [4]). In addition to the $t - W^{\pm}$ penguin loop, which is responsible for the $b \to s\gamma$ decay in the Standard Model, the MSSM allows for new contributions. These come from loops containing at least one charged particle, and include the top-charged Higgs contribution $t-H^{\pm}$, stop-chargino $\tilde{t}-\tilde{\chi}^{\pm}$ and sbottom-neutralino/gluino contributions $\tilde{\chi}^0-\tilde{b}$, $\tilde{g}-\tilde{b}$.

The flavor structure of the MSSM is not determined by symmetries and is generated by the soft SUSY breaking terms which can introduce many arbitrary parameters. They are severely constrained in models with minimal flavor violation (MFV), where the only source of flavor violation is the usual CKM matrix. The most general form of the squark mass matrices in the super-CKM basis can be written as (see, e.g., [5])

$$\mathcal{M}_U^2 = \begin{pmatrix} M^2_{U_{LL}} & M^2_{U_{LR}} \\ M^{2\dagger}_{U_{LR}} & M^2_{U_{RR}} \end{pmatrix}, \qquad \mathcal{M}_D^2 = \begin{pmatrix} M^2_{D_{LL}} & M^2_{D_{LR}} \\ M^{2\dagger}_{D_{LR}} & M^2_{D_{RR}} \end{pmatrix} \tag{1}$$

The 3×3 submatrices $M^2_{U_{ij}}$ and $M^2_{D_{ij}}$ are given in terms of the quark mass matrices and soft SUSY breaking terms $M^2_{\tilde{U}_{L,R}}$, $M^2_{\tilde{D}_{L,R}}$ and A_U, A_D defined as usual by

$$\mathcal{L}_{soft} = -\sum_{\tilde{Q}=\tilde{U}_L,\tilde{D}_L} \tilde{Q}^\dagger M^2_{\tilde{Q}_L}\tilde{Q} - \tilde{U}^\dagger M^2_{\tilde{U}_R}\tilde{U} - \tilde{D}^\dagger M^2_{\tilde{D}_R}\tilde{D} + \tilde{Q}A_U H_U\tilde{U} + \tilde{Q}A_D H_D\tilde{D}\,. \tag{2}$$

In MFV models the matrices A_U, A_D, $M^2_{\tilde{U}_R}$ and $M^2_{\tilde{D}_R}$ must be diagonal. Usually, this is taken to imply that the only contribution to $b\to s\gamma$ in MFV-MSSM is the top-charged Higgs diagram, which has the same chiral structure as the SM. In such a situation, the photon in $b\to s\gamma$ is again left-handed.

It was pointed out in [6] that MFV models actually allow nontrivial flavor violation in the squark sector. The matrices $M^2_{\tilde{U}_L}$ and $M^2_{\tilde{D}_L}$ are connected by SU(2) gauge invariance as $M^2_{\tilde{D}_L} = V^\dagger_{CKM}M^2_{\tilde{U}_L}V_{CKM}$, which implies that a diagonal, but not proportional to the unit matrix $M^2_{\tilde{D}_L}$, can give a non-diagonal structure for $M^2_{\tilde{U}_L}$ (and vice versa). This allows the chargino-up squark and neutralino/gluino-up squark contributions to $b\to s\gamma$. The latter graphs can occur with a helicity flip along the gluino line, which can produce a right-handed photon component in $b\to s\gamma$.

Relaxing the MFV constraints on the flavor structure (the so-called unconstrained MSSM) generally leaves the new physics contributions to $b\to s\gamma$ be dominated by the gluino graph, which can easily introduce a right-handed photon component. Data on the total $B\to X_s\gamma$ branching ratio set very stringent constraints on the allowed squark mass matrices [7]. An extreme way of satisfying such constraints in a generic MSSM has been proposed in [8], where it is suggested that the MSSM graphs exactly cancel the SM contribution to the left-handed penguin amplitude, in such a way that the right-handed amplitude precisely reproduces the observed rate. A measurement of the photon helicity in $b\to s\gamma$ will clearly help decide which of these possibilities (if any) is realized in Nature.

Several ways were suggested to look for signals of physics beyond the SM through photon helicity effects in $B \to X_s \gamma$. In the first suggested method [9] the photon helicity is probed through mixing-induced CP asymmetries. The sensitivity to the polarization comes from interference between B^0 and $\overline{B}^0$ decay amplitudes into a common state of definite photon polarization. However, measuring asymmetries at a level of a few percent, as expected in the SM, require an order of 10^9 B mesons which might not be available at the existing B factories for some time. In a second scheme one studies angular distributions in $B \to \gamma(\to e^+e^-)K^*(\to K\pi)$, where the photon can be virtual [10] or real, converting in the beam pipe to an electron-positron pair [12]. The efficiency of this method is comparable to that of the previous method. A somewhat different method was proposed in [11] and makes use of angular correlations in both exclusive and inclusive $\Lambda_b \to X_s \gamma$ decays.

We discuss in the following a method [13, 14, 15] for measuring the photon polarization using angular correlations in the strong decay products of a K resonance in $B \to K_{\rm res}\gamma$. Denoting with $A_{R,L}(\vec{p}_i)$ the amplitude for the strong decay of a $K_{\rm res}$ at rest in a spin state $|j, m = \pm 1\rangle$ into a final state $|f\rangle$ containing hadrons with momenta $\vec{p}_i$, one could ask what is the condition for a nonvanishing asymmetry $|A_R(\vec{p}_i)| \neq |A_L(\vec{p}_i)|$. This is a typical 'motion-reversal' asymmetry of the form

$$a^{T-odd}_{i\to f} \equiv |T_{i\to f}|^2 - |T_{P\bar{i}\to P\bar{f}}|^2 \tag{3}$$

where $\bar{i}$, $\bar{f}$ are motion-reversed states, changing the momenta and spins $(\vec{p}_i, s_i) \to (-\vec{p}_i, -s_i)$, and P is the parity operator. Since parity is conserved in strong interactions, one can replace $|T_{P\bar{i}\to P\bar{f}}| = |T_{\bar{i}\to\bar{f}}|$ on the right-hand side (this is equivalent to $|A_{R,L}(\vec{p}_i)| = |A_{R,L}(-\vec{p}_i)|$). T-invariance (or equivalently CP invariance) of the strong interactions gives $|T_{\bar{i}\to\bar{f}}| = |T_{f\to i}|$. Using this together with the unitarity condition $T^*_{i\to f} - T_{f\to i} = -i\sum_k T^*_{i\to k}T_{f\to k} \equiv -i\alpha_{i\to f}$ into (3) gives that the left/right asymmetry can be written as

$$a^{T-odd}_{i\to f} = 2\mathrm{Im}\,(T_{i\to f}\alpha_{i\to f}) - |\alpha_{i\to f}|^2\,. \tag{4}$$

If all decay amplitudes are real then $\alpha_{i\to f} = 0$ which shows that a nonvanishing asymmetry requires nontrivial final state interactions.

Furthermore, 2-body final states (e.g. $K\pi$) cannot produce an asymmetry because it is impossible to form a quantity which is odd under motion reversal from just two vectors $\vec{q}$ (photon momentum in the $K_{\rm res}$ frame) and $\hat{n}$ (the direction parameterizing the final state $|K(\hat{n})\pi(-\hat{n})\rangle$.

A nonvanishing asymmetry can be realized however in 3-body strong decays $K_{\rm res} \to K\pi\pi$. Such decays are realized for the lowest excitations of the K with quantum numbers $J^P = 1^-, 1^+, 2^+$, some of which have been recently observed to be produced in rare radiative decays. Both Belle and CLEO measured recently the decay $B \to K_2^*(1430)\gamma$ with a branching ratio of $(1.50^{+0.58+0.11}_{-0.53-0.13}) \times 10^{-5}$ and $(1.66^{+0.59}_{-0.53} \pm$

0.13) × 10^{-5}, respectively [16]. Similar branching ratios are expected from theoretical estimates for decays into $K_1(1400)$ and $K_1(1270)$ [17].

These states decay strongly to 3-body final $K\pi\pi$ states. Neglecting a small non-resonant contribution, these decays are dominated by interference of a few channels

$$K^+_{\rm res}\to\left\{\begin{array}{c} K^{*+}\pi^0 \\ K^{*0}\pi^+ \\ \rho^+K^0 \end{array}\right\}\to K^0\pi^+\pi^0\,,\qquad K^0_{\rm res}\to\left\{\begin{array}{c} K^{*+}\pi^- \\ K^{*0}\pi^0 \\ \rho^-K^+ \end{array}\right\}\to K^+\pi^-\pi^0\,. \tag{5}$$

The different channels $K^*\pi$ are related by isospin symmetry and contribute with a relative strong phase which can be parameterized in terms of Breit-Wigner forms. The $K_1(1400)$ decays predominantly to $K^*\pi$ in a mixture of S and D waves, with a branching ratio of 95% [18]. To a good approximation one can neglect the D wave component, which allows a parameter-free computation of the asymmetry. The smaller D-wave component and the $K\rho$ contribution can be also included using the measurements of the partial wave amplitudes and phases measured by the ACCMOR Collaboration [19].

The most convenient way of presenting the result for the polarization sensitive observable is in terms of an angular distribution in the rest frame of the resonance $K_{\rm res}$. Introducing the angle θ between the opposite of the photon momentum $-\vec{q}$ and the normal to the $K\pi\pi$ decay plane defined as $\vec{p}_{\rm slow}\times\vec{p}_{\rm fast}$, where $\vec{p}_{\rm slow}$ and $\vec{p}_{\rm fast}$ are the momenta of the slower and faster pions, this is given by [15]

$$\begin{aligned}\frac{{\rm d}^2\Gamma}{{\rm d}s\,{\rm d}\cos\tilde{\theta}} &= |c_1|^2\left\{1+\cos^2\tilde{\theta}+4P_\gamma R_1\cos\tilde{\theta}\right\} \qquad (6)\\ &+\ |c_2|^2\left\{\cos^2\tilde{\theta}+\cos^2 2\tilde{\theta}+12P_\gamma R_2\cos\tilde{\theta}\cos 2\tilde{\theta}\right\}+|c_3|^2 B_{K_1^*}(s)\sin^2\tilde{\theta}\\ &+\ \left\{c_{12}\frac{1}{2}(3\cos^2\tilde{\theta}-1)+P_\gamma c'_{12}\cos^3\tilde{\theta}\right\}\,,\end{aligned}$$

where the first three terms are produced by decays through $K_{\rm res}$ resonances with $J^P=1^+,2^+$ and 1^-, and the last terms come from 1^+-2^+ interference. The hadronic parameters $R_{1,2}$ can be computed with relatively small model dependence as explained above, which gives [14, 15] $R_1=0.22\pm0.03$, $R_2=0.01-0.05$. Thus, measurements of the angular distribution (6) can be used to extract the photon polarization parameter P_γ.

Assuming an exclusive B branching ratio into $K_1(1400)\gamma$ of 0.7×10^{-5} and assuming that the final states in (5) are detected through $K^+\pi^-\pi^0$ and $K_S\pi^+\pi^0$ implies that about 2×10^7 $B\overline{B}$ pairs are required to measure 80 $K\pi\pi\gamma$ events which should be sufficient for a 3σ confirmation of a left-handed photon in $b\to s\gamma$ decay. Such a measurement should be feasible at the existing B factories in the near future.

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