Measuring the Photon Polarization in $B \to K\pi\pi\gamma$

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(Received 7 August 2001; revised manuscript received 16 November 2001; published 22 January 2002)

We propose a way of measuring the photon polarization in radiative B decays into K resonance states decaying to $K\pi\pi$, which can test the standard model and probe new physics. The photon polarization is shown to be measured by the up-down asymmetry of the photon direction relative to the $K\pi\pi$ decay plane in the K resonance rest frame. The integrated asymmetry in $K_1(1400) \to K\pi\pi$, calculated to be 0.34 ± 0.05 in the standard model, is measurable at currently operating B factories.

DOI: 10.1103/PhysRevLett.88.051802 PACS numbers: 13.25.Hw, 13.40.Hq, 13.88.+e

The standard model (SM) predicts that photons emitted in rare $b \to s\gamma$ decays are left-handed [1], up to small corrections of order m_s/m_b, while being right-handed in $\bar{b} \to \bar{s}\gamma$. This feature is common to inclusive and exclusive radiative decays, also when including long-distance effects in the latter case [2]. While measurements of the inclusive rate agree reasonably well with SM calculations [1], no evidence exists for the helicity of the photons in these decays. In several models beyond the SM, the photon in $b \to s\gamma$ acquires an appreciable right-handed component due to the exchange of a heavy fermion in the electroweak loop process. For instance, in $SU(2)_L \times SU(2)_R \times U(1)$ left-right symmetric models [3], this component may be comparable in magnitude to the left-handed component, without affecting the SM prediction for the inclusive radiative decay rate. An independent measurement of the photon helicity is therefore of interest.

Several strategies have been proposed to look for signals of physics beyond the SM through helicity effects in $B \to X_s\gamma$. In one method, the photon helicity is probed through mixing-induced CP asymmetries [4]. In two other schemes, one studies angular distributions in radiative decays of Λ_b baryons [5,6] and in $B \to \gamma(\to e^+e^-)K^*(\to K\pi)$ [7,8]. The methods using B mesons are sensitive to interference between amplitudes involving photons with left- and right-handed polarization. In the SM the interference is at a level of a few percent, and these methods become unfeasible at present B factories also for larger interference due to insufficient luminosities. The methods using Λ_b decays, measuring directly the photon polarization, rely on future hadron colliders or on extremely high luminosity e^+e^- Z factories.

In the present Letter, we propose to measure the photon polarization in exclusive radiative B decays to kaon resonance states, $B \to K_{\mathrm{res}}\gamma$. We will study in particular decays into an axial-vector meson, $K_1(1400)$, and into a tensor meson, $K_2^*(1430)$. This measurement will be shown to be feasible at currently operating B factories. An earlier suggestion to look for parity violation in $B \to K_1(1400)\gamma$ was made in [9]. Radiative decays into $K_2^*(1430)$ were observed both by the CLEO [10] and Belle [11] collaborations with branching ratios around 10^{-5}. In these experiments K_2^* states were identified through the $K\pi$ decay mode. K_1 states, which do not decay in this mode, are expected to be observed in the $K\pi\pi$ channel. As we will argue below, in order to probe the photon helicity, one must study excited kaon decays into final states involving at least three particles.

Let us explain first the necessary conditions for a theoretically clean measurement of the photon helicity in radiative B decays from recoil hadron distributions. Since the photon helicity is odd under parity, and since one measures only the momenta of final decay products, spin information cannot be obtained from two body decays of the excited kaon. It requires at least a three body decay in which one can form a parity-odd triple product $\vec{p}_\gamma \cdot (\vec{p}_1 \times \vec{p}_2)$. Here $\vec{p}_\gamma$ is the photon momentum, and $\vec{p}_1, \vec{p}_2$ are two of the final hadron momenta, all measured in the K-resonance rest frame. The average value of the triple product has one sign for a left-handed photon and an opposite sign for a right-handed photon.

The above correlation is, however, also T odd. In order not to violate time reversal in the excited kaon decay, the decay amplitude must involve nontrivial final state interactions. Usually this poses the difficulty of introducing an unknown final state phase. In order to have a measurement which can be cleanly interpreted in terms of the photon helicity, this phase difference must be calculable. This is the case in $K_{\mathrm{res}} \to K^*\pi \to K\pi\pi$, where two isospin-related $K^*(892)$ resonance amplitudes interfere. Parametrizing resonance amplitudes in terms of Breit-Wigner forms, known to be a very good approximation for the narrow K^*, yields a calculable strong phase. In this respect, this method is similar to measuring the τ neutrino helicity

 0031-9007/02/88(5)/051802(4)$20.00

in $\tau \to a_1 \nu_\tau$, where the corresponding phase difference is calculable in terms of the two interfering $a_1 \to \rho\pi$ amplitudes [12,13].

Considering cascade decays of $\bar{B}(b\bar{q})$ $(q = u, d)$, $\bar{B} \to \bar{K}_{\rm res}\gamma \to \bar{K}\pi\pi\gamma$, we denote weak $\bar{B} \to \bar{K}_{\rm res}\gamma$ amplitudes involving left- and right-handed photons by c_L and c_R, and corresponding strong $\bar{K}_{\rm res}$ decay amplitudes by $\mathcal{M}_L$ and $\mathcal{M}_R$, respectively. Amplitudes involving left- and right-handed photons do not interfere since *in principle* the photon polarization is measurable. Therefore,

$$|A(\bar{B} \to \bar{K}_{\rm res}\gamma, \bar{K}_{\rm res} \to \bar{K}\pi\pi)|^2 = |c_L|^2|\mathcal{M}_L|^2 + |c_R|^2|\mathcal{M}_R|^2. \quad (1)$$

In the SM, the photon in $\bar{B}$ decays is dominantly left-handed, $|c_R|^2 \ll |c_L|^2$. The corresponding B decay amplitudes obey a reversed hierarchy implying a right-handed photon. We denote the photon polarization by λ_γ,

$$\lambda_\gamma \equiv \frac{|c_R|^2 - |c_L|^2}{|c_R|^2 + |c_L|^2}, \quad (2)$$

such that in the SM $\lambda_\gamma \approx 1$ holds for radiative B decays, while $\lambda_\gamma \approx -1$ applies to $\bar{B}$ decays.

The weak amplitudes $c_{R,L}$ are given by $c_{R,L} = g_+^{K_{\rm res}}(0)C_{7R,L}$, where $g_+^{K_{\rm res}}(0)$ are hadronic form factors at $q^2 = 0$, which have already been computed using several models [14]. (For the most part, we will not rely on these calculations). $C_{7R,L}$ are Wilson coefficients appearing in the effective weak radiative Hamiltonian,

$$\mathcal{H}_{\rm rad} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^*(C_{7R}\mathcal{O}_{7R} + C_{7L}\mathcal{O}_{7L}),$$
$$\mathcal{O}_{7L,R} = \frac{e}{16\pi^2} m_b \bar{s}\sigma_{\mu\nu}\frac{1 \pm \gamma_5}{2} bF^{\mu\nu}. \quad (3)$$

Since the form factors $g_+^{K_{\rm res}}$ are common to c_L and c_R, a measurement of the ratio c_R/c_L can be translated into information about the underlying new physics entering the Wilson coefficients.

We now describe details of the method based on the decays $B \to K_1\gamma$, beginning with formalism and ending with an estimate demonstrating the high sensitivity of the measurement to the photon polarization. We compare this sensitivity with the one using $K\pi\pi$ decays of K_2^*.

The decay processes $K_1(1400) \to K\pi\pi$ are dominated by $K^*(892)\pi$, with a branching ratio of $94 \pm 6\%$ [15]. A smaller branching ratio into ρK, $3 \pm 3\%$ [15], will be neglected at this point, and will be considered later on in order to estimate an uncertainty. We will study the modes

$$K_1^+ \to \left\{\begin{matrix} K^{*+}\pi^0 \\ K^{*0}\pi^+ \end{matrix}\right\} \to K^0\pi^+\pi^0,$$
$$K_1^0 \to \left\{\begin{matrix} K^{*+}\pi^- \\ K^{*0}\pi^0 \end{matrix}\right\} \to K^+\pi^-\pi^0. \quad (4)$$

The decay amplitude of $K_1(1400) \to K^*(892)\pi$ can be written in terms of two invariant amplitudes,

$$\mathcal{M}_1 = A(\varepsilon \cdot \varepsilon') + B(\varepsilon \cdot p')(\varepsilon'^* \cdot p), \quad (5)$$

where ε, p and ε', p' are the polarization vectors and momenta of the K_1 and K^*, respectively. This amplitude is a mixture of S and D waves. The D/S ratio of widths and the phase difference between the two partial wave amplitudes were measured in [16], $|A_D/A_S|^2 = 0.04 \pm 0.01$ and $\arg(A_D/A_S) \equiv \delta_D - \delta_S = (260 \pm 20)°$, respectively. The relation between the invariant amplitudes and the partial wave amplitudes can be shown to be given by [17]

$$A = A_S + \frac{1}{\sqrt{2}} A_D,$$
$$B = \left[-\left(1 - \frac{m_{K^*}}{E_{K^*}}\right)A_S - \left(1 + 2\frac{m_{K^*}}{E_{K^*}}\right)\frac{1}{\sqrt{2}} A_D\right] \times \frac{E_{K^*}}{M_{K_1}\vec{p}_{K^*}^{\,2}}, \quad (6)$$

where the K^* energy and momentum are given in the K_1 rest frame. The amplitude (5) must be convoluted with the amplitude for $K^* \to K\pi$ which is proportional to $\varepsilon' \cdot (p_\pi - p_K)$. Isospin symmetry implies that the two K^* contributions to the processes (4) are antisymmetric under the exchange of the two pion momenta.

Denoting the momentum of K_1, the two pion momenta and the kaon momentum by p, p_1, p_2, and p_3, respectively, we find the amplitude of (4):

$$\mathcal{M} = \varepsilon^\mu J_\mu, \qquad J_\mu = C(s_{13}, s_{23})p_{1\mu} - (p_1 \leftrightarrow p_2), \quad (7)$$

where

$$C(s_{13}, s_{23}) \propto A\left[\left(1 - \frac{m_K^2 - m_\pi^2}{m_{K^*}^2}\right)B_{23}^{K^*} - 2B_{13}^{K^*}\right] + B\left[\left(1 - \frac{m_K^2 - m_\pi^2}{m_{K^*}^2}\right)(p \cdot p_1 - m_\pi^2) - 2p_1 \cdot p_2\right]B_{23}^{K^*}, \quad (8)$$

and $B_{ij}^{K^*}$ is a Breit-Wigner form,

$$B_{ij}^{K^*} = (s_{ij} - m_{K^*}^2 - im_{K^*}\Gamma_{K^*})^{-1},$$
$$s_{ij} = (p_i + p_j)^2. \quad (9)$$

$p \cdot p_1$ and $p_1 \cdot p_2$ can be written in terms of s_{13} and s_{23}. Using (6), one obtains

$$C(s_{13}, s_{23}) \propto \left[\left(1 - \frac{m_K^2 - m_\pi^2}{m_{K^*}^2}\right)B_{23}^{K^*} - 2B_{13}^{K^*}\right] + \kappa\left[\left(1 - \frac{m_K^2 - m_\pi^2}{m_{K^*}^2}\right)(p \cdot p_1 - m_\pi^2) - 2p_1 \cdot p_2\right]B_{23}^{K^*}, \quad (10)$$

where $\kappa = B/A = -[0.38 + 8.67|A_D/A_S|e^{i(\delta_D - \delta_S)}] \times [1 + 0.71|A_D/A_S|e^{i(\delta_D - \delta_S)}]^{-1}$ GeV^{-2}.

Let us express the amplitudes $\mathcal{M}_{L,R}$ in the rest frame of the K_1. The polarization vectors corresponding to right- and left-handed K_1 of helicity ± 1, $\varepsilon^{\mu}_{\pm 1}$, are defined in this frame by $\varepsilon^0_{\pm 1} = 0$, and $\vec{\varepsilon}_{\pm 1} = \mp(1/\sqrt{2})(\hat{e}_x \pm i\hat{e}_y)$. The two unit vectors $\hat{e}_x$ and $\hat{e}_y$ are perpendicular to $\hat{e}_z = -\hat{p}_\gamma$, which points along a direction opposite to the photon (or B) momentum. Denoting by θ the angle between the normal to the decay plane, $\hat{n} \equiv (\vec{p}_1 \times \vec{p}_2)/|(\vec{p}_1 \times \vec{p}_2)|$, and the direction opposite to the photon, $\cos\theta = \hat{n} \cdot \hat{e}_z$, one finds

$$\mathcal{M}_{R,L} \propto \frac{1}{\sqrt{2}}(\mp J_x - i\cos\theta J_{y'}), \tag{11}$$

where x, y', and $\hat{n}$ form a set of orthogonal axes. (We choose these axes such that the plane perpendicular to the photon direction and the decay plane intersect on the x axis.)

Squaring the amplitudes and integrating over a common rotation angle ϕ of $\vec{p}_1$ and $\vec{p}_2$ in the decay plane, one obtains

$$\frac{1}{2\pi}\int_0^{2\pi} d\phi |\mathcal{M}_{R,L}|^2 \propto |\vec{J}|^2(1 + \cos^2\theta) \pm 2\,\mathrm{Im}[\hat{n} \cdot (\vec{J} \times \vec{J}^*)]\cos\theta. \tag{12}$$

Using Eqs. (1) and (2), one obtains the $B \to (K\pi\pi)_{K_1}\gamma$ decay distribution:

$$\frac{d\Gamma}{ds_{13}ds_{23}d\cos\theta} \propto |\vec{J}|^2(1 + \cos^2\theta) + \lambda_\gamma 2\,\mathrm{Im}[\hat{n} \cdot (\vec{J} \times \vec{J}^*)]\cos\theta. \tag{13}$$

Since the angular variable $\cos\theta$ changes sign under the exchange of s_{13} and s_{23}, we define a new angle $\tilde{\theta}$ which is independent of s_{13} and s_{23}, $\cos\theta \equiv \mathrm{sgn}(s_{13} - s_{23})\cos\tilde{\theta}$. An equivalent definition of $\tilde{\theta}$ is the angle between $-\vec{p}_\gamma$ and the normal to the decay plane defined by $\vec{p}_{\mathrm{slow}} \times \vec{p}_{\mathrm{fast}}$, where $\vec{p}_{\mathrm{slow}}$ and $\vec{p}_{\mathrm{fast}}$ are the momenta of the slower and the faster pions.

The asymmetry between decay distributions corresponding to right- and left-handed photons, from which the photon polarization can be determined, is contained in the second term in Eq. (13). It describes an up-down asymmetry of the photon momentum with respect to the K_1 decay plane. In order to measure λ_γ, one would fit the B and $\bar{B}$ decay distributions to (13), which has a well-defined dependence on θ and on the energy variables s_{13}, s_{23} occurring in the Breit-Wigner forms. In order to obtain a conservative estimate for the sensitivity of the decay distribution to the photon polarization, let us consider the integrated up-down asymmetry,

$$\mathcal{A} = \frac{\int_0^{\pi/2} \frac{d\Gamma}{d\cos\tilde{\theta}} d\cos\tilde{\theta} - \int_{\pi/2}^{\pi} \frac{d\Gamma}{d\cos\tilde{\theta}} d\cos\tilde{\theta}}{\int_0^{\pi} \frac{d\Gamma}{d\cos\tilde{\theta}} d\cos\tilde{\theta}} = \frac{3}{4}\frac{\langle \mathrm{Im}[\hat{n} \cdot (\vec{J} \times \vec{J}^*)]\,\mathrm{sgn}(s_{13} - s_{23})\rangle}{\langle |\vec{J}|^2 \rangle}\lambda_\gamma. \tag{14}$$

Integrating the numerator and denominator over the entire Dalitz plot, one obtains

$$\mathcal{A} = (0.34 \pm 0.05)\lambda_\gamma. \tag{15}$$

The calculated asymmetry involves theoretical uncertainties from two sources: the ρK intermediate state which we neglected, and an error in the D-wave amplitude of $K_1 \to K^*\pi$. Varying the magnitude of the $K_1\rho K$ coupling under the constraint from the measured $K_1(1400) \to K\rho$ branching ratio, $\mathcal{B}(K_1 \to K\rho) = 0.03 \pm 0.03$, and varying the relative intrinsic phase between the ρK and the $K^*\pi$ amplitudes in the range $-30°$ to $+30°$ as measured in [16], this amplitude introduces an uncertainty of ± 0.04 in $\mathcal{A}$. The experimental error in the D wave amplitude is shown to contribute ± 0.03 to this uncertainty when varying $|A_D/A_S|^2 = 0.04 \pm 0.01, \delta_D - \delta_S = 260° \pm 20°$ [16].

The SM predicts $\lambda_\gamma \approx +1(-1)$ for $B(\bar{B})$ decays. Namely, *in B^- and $\bar{B}^0$ decays, the photon prefers to move in the hemisphere of $\vec{p}_{\mathrm{slow}} \times \vec{p}_{\mathrm{fast}}$, while in B^+ and B^0 decays it prefers to move in the opposite direction.* For a three standard deviation measurement of a total up-down asymmetry, $\mathcal{A} \simeq 0.34$ (-0.34), expected in the SM for $B^+(B^-)$ and $B^0(\bar{B}^0)$ decays, one needs to observe a total of about 80 charged and neutral B and $\bar{B}$ decays to $(K\pi\pi)_{K_1}\gamma$. In order to estimate the number of $B\bar{B}$ pairs needed for this measurement, we will assume that the branching ratio of $B \to K_1(1400)\gamma$ is 0.7×10^{-5}, as calculated in some models [14]. We use $\mathcal{B}[K_1(1400) \to K^*\pi] = 0.94$ [15], and note that 4/9 of all $K^*\pi$ events in K_1^+ and K_1^0 decays occur in the two channels specified in Eq. (4). Including a factor 1/3 for observing a K_S (from K^0) through its $\pi^+\pi^-$ decay, we estimate a branching ratio of $\mathcal{B} = 0.7 \times 10^{-5} \times (4/9)0.94 \simeq 0.3 \times 10^{-5}$ into $(K^+\pi^-\pi^0)_{K_1(1400)}$ and $\mathcal{B} \simeq 0.1 \times 10^{-5}$ into $(K_S\pi^+\pi^0)_{K_1(1400)}$. Ignoring experimental efficiencies and background, 80 $(K\pi\pi)_{K_1}\gamma$ events can be obtained from a total of $2 \times 10^7 B\bar{B}$ pairs, including charged and neutrals. This number of B mesons has already been produced at e^+e^- colliders [18–20]. Since we ignored experimental efficiencies, resolution, and background, one may have to wait a year or so before obtaining the required number of events.

Similar studies can be carried out for other kaon resonance states in radiative B decays. The decay distribution for an excited K_1^* is insensitive to the photon polarization. In the case of $K_2^*(1430)$ one finds, when both $K^*\pi$ and ρK contributions are included,

$$\frac{d\Gamma}{ds_{13}ds_{23}d\cos\theta} = |\vec{p}_1 \times \vec{p}_2|^2\{|\vec{J}|^2(\cos^2\theta + \cos^2 2\theta) + \lambda_\gamma 2\,\mathrm{Im}[\hat{n} \cdot (\vec{J} \times \vec{J}^*)]\cos\theta\cos 2\theta\}, \tag{16}$$

where $\vec{J} = \vec{p}_1[B_{23}^{K^*} + \kappa_\rho B_{12}^{\rho}] + \vec{p}_2[B_{13}^{K^*} + \kappa_\rho B_{12}^{\rho}]$ and B_{12}^{ρ} is defined analogously to $B_{ij}^{K^*}$. The complex parameter κ_ρ, parametrizing the relative strength and final state phase difference of the $K^*\pi$ and ρK contributions, is given by

$$\kappa_\rho = |\kappa_\rho| e^{i\delta} = \sqrt{\frac{3}{2}}\,\frac{g_{K_2^*\rho K}}{g_{K_2^* K^* \pi}} \cdot \frac{g_{\rho\pi\pi}}{g_{K^* K \pi}} \simeq 2.38 \,. \quad (17)$$

The two ratios of couplings are obtained from the corresponding measured partial widths [15]. The strong phase δ vanishes in the SU(3) limit and is dominated by the phase of $g_{K_2^*\rho K}/g_{K_2^* K^*\pi}$, measured to be smaller than 30° in a K_2^* resonance production experiment [16].

While the integrated up-down asymmetry in Eq. (16) vanishes, a useful observable which is proportional to λ_γ is $\langle \cos\tilde{\theta} \rangle$. Integrating this quantity over a square region, 0.71 GeV$^2 \le s_{13}, s_{23} \le 0.89$ GeV^2, where the two K^* bands of widths $2\Gamma_{K^*}$ overlap, one finds $\langle \cos\tilde{\theta} \rangle_s = (0.071 \pm 0.03)\lambda_\gamma$, when δ is varied in the range (0° ± 30°). The value of $\langle \cos\tilde{\theta} \rangle$ obtained when integrating over the entire Dalitz plot is considerably smaller.

We conclude with a few practical comments. The region of $K\pi\pi$ invariant mass around 1400 MeV includes $K_1(1400)$ which involves the large up-down asymmetry calculated in (15), $K_1^*(1410)$ which leads to no asymmetry, and $K_2^*(1430)$ which adds a relatively small asymmetry. The two asymmetries from K_1 and K_2^* have equal signs. Therefore, the sign of the total asymmetry is predicted in the SM. Using the different energy and angular dependence of the three resonances, one should be able to isolate the K_1 contribution from the other resonances and from a small nonresonant $K\pi\pi$ contribution in a narrow invariant mass band around $m(K\pi\pi) = 1400$ MeV. This would provide a first significant photon polarization measurement in radiative $b \to s\gamma$ decays, which may confirm the SM prediction or detect a *large violation* of this prediction. A precise measurement, sensitive to *small* new physics effects, seems unfeasible at this time.

Our study focused on decay modes of higher K resonances which involve one neutral pion. This was necessary in order to have two interfering $K^*\pi$ amplitudes which are related by isospin symmetry. An asymmetry is also expected in channels involving only charged particles, $K^\pm\pi^\mp\pi^\pm$, which were measured very recently by the Belle collaboration [11]. In this case, the asymmetry originates in the interference between $K^*\pi$ and ρK (or $f_0 K$) amplitudes. The latter amplitude is significant in $K_1(1270)$ and $K_2^*(1430)$ decays. In $K_1(1270) \to K^*\pi$, one must also consider the effect of a possibly significant D-wave amplitude, for which the upper limit is rather loose [15,16].

We thank A. Weinstein for useful correspondence and for sending us his unpublished paper [9]. D. P. is grateful to the Technion physics department, and M. G. wishes to thank the SLAC theory group for its kind hospitality. This work was supported in part by the Israel Science Foundation founded by the Israel Academy of Sciences and Humanities, by the U.S.–Israel Binational Science Foundation through Grant No. 98-00237, and by the DOE under Grant No. DOE-FG03-97ER40546.

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