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Photon polarization in $B \to K^*\gamma$

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The polarization of the outgoing photon in the decay process $B \to K^*\gamma$ followed by the decay process $K^* \to K\pi$ is considered and it is shown that information on form factors in the B decay can be obtained through the photon polarization.

The rare decay process $B \to K^*\gamma$ has attracted a great deal of attention recently because it occurs through the loop-induced amplitude $b \to s\gamma$ (Ref. 1) and hence might give a new test of higher-order correction to the standard model together with some information on the top-quark mass. The purpose of this Brief Report is to consider the polarization of the outgoing photon in $B \to K^*\gamma$.

The exclusive decay process $B \to K^*\gamma$ can be described by the transition amplitude[2-4]

$$\begin{aligned} M = {} & C\varepsilon^{\mu *}(q,\lambda) \\ & \times\{iF_1\varepsilon_{\mu\nu\alpha\beta}\varepsilon^{\nu *}(k,\kappa)(p+k)^\alpha q^\beta \\ & + F_2[\Delta\varepsilon^*_\mu(k,\kappa) - \varepsilon^*(k,\kappa)\cdot q(p+k)_\mu]\} \ , \end{aligned} \tag{1}$$

where $\varepsilon^\mu(q,\lambda)$ and $\varepsilon^\mu(k,\kappa)$ are wave vectors of photon and K^*; p, k, and q are momenta of B, K^*, and photon, respectively, and Δ is $(m_B^2 - m_{K^*}^2)$. The form factors $F_1(q^2)$ and $F_2(q^2)$ are predicted model dependently, e.g., in Ref. 2 they are predicted to be equal:

$$F_1(0) = F_2(0) \simeq 0.115 \ ; \tag{2}$$

in Ref. 3 monopole form factors are considered, and also different q^2 dependence is considered for $F_1(q^2)$ and $F_2(q^2)$ in Ref. 4. The constant C in Eq. (1) contains the dependence on the Cabibbo-Kobayashi-Maskawa (CKM) angles and heavy-quark masses as

$$C = \frac{eG_F}{4\sqrt{2}\pi^2} V_{tb}V^*_{ts}F(m_t)m_b \ , \tag{3}$$

and $F(m_t)$ was given in Refs. 5 and 6. These previous works are mostly concerned with the decay rate or branching ratio and, therefore, $|F_1|^2 + |F_2|^2$ as well as the overall factor C in the transition amplitude due to the QCD loop correction. Recently an experimental search for decays $B \to K^*\gamma$ has been performed by the ARGUS Collaboration.[7] The polarizations of hard photons, on the other hand, give more information on the relative values of two form factors.

The $B \to K^*\gamma$ process is followed consecutively by the strong decay process $K^* \to K\pi$ mostly (Ref. 8) which can be described by the transition amplitude

$$M' = f\varepsilon^\mu(k,\kappa)(p_K - \tilde{q})_\mu \ , \tag{4}$$

where f is a coupling constant, and p_K and $\tilde{q}$ are momenta of decay products K and π. The decay distribution of K^* is determined from

$$|M'|^2 = 4|f|^2\langle\varepsilon^\mu\varepsilon^{\nu *}\rangle\tilde{q}_\mu\tilde{q}_\nu , \tag{5}$$

where $\langle\varepsilon^\mu\varepsilon^{*\nu}\rangle$, the density matrix of K^*, can be obtained[9] from the production process described by Eq. (1). That is, Eq. (1) gives the (unnormalized) wave vector of K^* as

$$\begin{aligned} \varepsilon^\mu = {} & \varepsilon^{\rho *}(q,\lambda)\{iF_1\varepsilon_{\rho\sigma\alpha\beta}(p+k)^\alpha q^\beta \\ & + F_2[\Delta g_{\rho\sigma} - (p+k)_\rho q_\sigma]\} \\ & \times\sum_\kappa \varepsilon^{\sigma *}(k,\kappa)\varepsilon^\mu(k,\kappa) \ , \end{aligned} \tag{6}$$

where one can use

$$\sum_\kappa \varepsilon^{\sigma *}(k,\kappa)\varepsilon^\mu(k,\kappa) = I^{\mu\sigma} = \left(-g^{\mu\sigma} + \frac{k^\mu k^\sigma}{M^2_{K^*}}\right) \ . \tag{7}$$

Using Eq. (6) for $\langle\varepsilon^\mu\varepsilon^{*\nu}\rangle$ in Eq. (5), one obtains

$$\begin{aligned} |M'|^2(\lambda,\lambda') \propto {} & 4C^2|f|^2\varepsilon^\xi(q,\lambda')\varepsilon^{\eta *}(q,\lambda) \\ & \times[4|F_1|^2\varepsilon_\xi(\tilde{q}kq)\varepsilon_\eta(\tilde{q}kq) + |F_2|^2\Delta^2 J_\xi(\tilde{q})J_\eta(\tilde{q}) - 2iF_1^*F_2\Delta\varepsilon_\xi(\tilde{q}kq)J_\eta(\tilde{q}) + 2iF_1F_2^*\Delta\varepsilon_\eta(\tilde{q}kq)J_\xi(\tilde{q})] \ , \end{aligned} \tag{8}$$

where $J_\xi(\tilde{q})$ and $\varepsilon_\xi(\tilde{q}kq)$ are defined as

$$J_\xi(\tilde{q}) = \left(\tilde{q}_\xi - \frac{2q\cdot\tilde{q}}{\Delta}k_\xi\right) \ , \tag{9}$$

$$\varepsilon_\xi(\tilde{q}kq) = \varepsilon_{\xi\alpha\beta\gamma}\tilde{q}^\alpha k^\beta q^\gamma \ . \tag{10}$$

To obtain the outgoing photon polarization in the process, our method[10] in treating photon polarization is applied, i.e., replace $\varepsilon^{\xi}(q,\lambda')\varepsilon^{\eta *}(q,\lambda)$ in the equation by

$$\varepsilon^{i}(q,\lambda')\varepsilon^{j*}(q,\lambda)=\frac{1}{2}\left((\delta^{ij}-\hat{q}^{i}\hat{q}^{j})\delta_{\lambda'\lambda}-\frac{i}{2}(\lambda'+\lambda)\epsilon^{ijk}\hat{q}^{k} -\frac{i}{2}(\lambda'-\lambda)[\hat{a}^{i}(\hat{\mathbf{q}}\times\hat{\mathbf{a}})^{j}+\hat{a}^{j}(\hat{\mathbf{q}}\times\hat{\mathbf{a}})^{i}]+\frac{1}{2}(\lambda'\lambda-1)[\hat{a}^{i}\hat{a}^{j}-(\hat{\mathbf{q}}\times\hat{\mathbf{a}})^{i}(\hat{\mathbf{q}}\times\hat{\mathbf{a}})^{j}]\right), \quad (11)$$

where $\hat{\mathbf{q}}$ is the unit vector along $\mathbf{q}$ and $\hat{\mathbf{a}}$ is a unit vector perpendicular to $\mathbf{q}$.

In the B rest frame, the production and decay processes of K^* can occur in a plane and one chooses $\hat{\mathbf{a}}$ normal to the plane, i.e.,

$$\hat{\mathbf{a}}=\frac{\mathbf{q}\times\tilde{\mathbf{q}}}{|\mathbf{q}\times\tilde{\mathbf{q}}|}. \quad (12)$$

Then the photon polarization can be obtained through the Stokes parameters ξ_i $(i=1,2,3)$ which are contained in the photon density matrix in the helicity basis as

$$\rho_{\lambda\lambda'}=\frac{1}{2}\left(\delta_{\lambda\lambda'}+\frac{i}{2}\xi_1(\lambda-\lambda')+\frac{1}{2}\xi_2(\lambda+\lambda')+\frac{1}{2}\xi_3(\lambda\lambda'-1)\right),$$

or

$$\rho=\frac{1}{2}\begin{pmatrix}1+\xi_2 & -\xi_3+i\xi_1\\ -\xi_3-i\xi_1 & 1-\xi_2\end{pmatrix}. \quad (13)$$

Explicitly they are obtained from

$$|M|^2(B\to K^*\gamma\to K\pi\gamma)\propto 4C^2|f|^2(|F_1|^2+|F_2|^2)A\frac{1}{2}\left(\delta_{\lambda\lambda'}-\frac{2\,\mathrm{Re}(F_1F_2^*)}{|F_1|^2+|F_2|^2}\frac{1}{2}(\lambda+\lambda')+\frac{2\,\mathrm{Im}(F_1F_2^*)}{|F_1|^2+|F_2|^2}\frac{i}{2}(\lambda-\lambda') +\frac{|F_1|^2-|F_2|^2}{|F_1|^2+|F_2|^2}\frac{1}{2}(\lambda\lambda'-1)\right), \quad (14)$$

where A is defined as

$$A=[4\Delta q\cdot\tilde{q}k\cdot\tilde{q}-4M_{K^*}^2(q\cdot\tilde{q})^2-M_\pi^2\Delta^2] =\Delta^2|\tilde{\mathbf{q}}|^2\sin^2\theta, \quad (15)$$

and θ is the angle between outgoing photon and pion, one of K^* decay products. Therefore, the Stokes parameters ξ_i which characterize the polarization of the outgoing photon become

$$\xi_2=-\frac{2\,\mathrm{Re}(F_1F_2^*)}{|F_1|^2+|F_2|^2}, \quad (16)$$

$$\xi_1=\frac{2\,\mathrm{Im}(F_1F_2^*)}{|F_1|^2+|F_2|^2}, \quad (17)$$

$$\xi_3=\frac{|F_1|^2-|F_2|^2}{|F_1|^2+|F_2|^2}, \quad (18)$$

and

$$\xi_1^2+\xi_2^2+\xi_3^2=1. \quad (19)$$

Therefore, if F_1 and F_2 are equal and real as in Ref. 2, the outgoing photon is completely circularly polarized. Otherwise,[3,4] the degree of circular polarization decreases and the outgoing photon is partly linearly polarized. Thus investigation of outgoing photon polarization might give additional information concerning the explicit values of form factors, their magnitude as well as q^2 dependence, in the $B\to K^*\gamma$ decay process.

The form factors can be studied through other transitions of $B\to D^*$ and $D\to K^*$ (Refs. 3, 4, 11, and 12). If these form factors are determined experimentally, one can distinguish the validity of the various quark-model predictions.

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