Probing right-handed currents in $B \to K^* \ell^+ \ell^-$ transitions

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Abstract

We discuss a possibility to probe right-handed weak hadronic currents in rare semileptonic $b \to s$ transitions. It is shown that within models involving right-handed as well as left-handed quark currents (LR models) one can expect a strong enhancement of the right-handed $K^*$ production in $B \to K^* \ell^+ \ell^-$ decays compared with models including only left-handed quark currents (SM, MSSM). Hence an experimental study of the transverse asymmetry of the produced $K^*$ mesons provides a clear test of the presence of the right-handed quark currents and a possibility to discriminate between the MSSM and LR extensions of the SM. At the same time, MSSM and LR models are found to yield qualitatively the same type of deviations from the SM in the forward-backward and the longitudinal lepton polarization asymmetries.
The interest in rare FCNC $B$ decays is motivated to a large extent by the fact that these decays provide a possibility to probe the new physics effects at comparatively low energies. However, for the experimental study of new physics effects it is important to have clear signatures for some particular extensions of the SM. Among possible extensions the most popular ones are the MSSM and LR models \[1, 2, 3, 4\]. Recently, it has been observed \[5\] that e.g. the MSSM extension of the SM can be probed by the analysis of the forward-backward ($A_{FB}$) and lepton polarization ($P_L$) asymmetries: namely, there are regions in the MSSM parameter space which yield qualitatively different behaviors of $A_{FB}$ and $P_L$ compared with the SM predictions.

Moreover, a possibility to probe the RH currents in $B \rightarrow K^{*} \nu \bar{\nu}$ decays has been recently pointed out in \[6\]. In this letter we discuss a possibility to discriminate between the MSSM and LR models by a study of the $q^2$-distributions of the transversely polarized $K^*$ mesons produced in the $B \rightarrow K^* \ell^+ \ell^-$ decays.

As it is known \[4\], the parameter space of the LR models is rather wide and although the CLEO results on rare radiative decays provide some restrictions on the values of the LR model parameters, much freedom is still left. We report that there are regions in the LR model parameter space still allowed by the CLEO data, which yield a strong enhancement of the right-handed $K^*$ produced in rare semileptonic (SL) $B \rightarrow K^*$ transitions. This contrasts to the predictions of other models where the RH quark currents are absent (SM, MSSM) and a strong dominance of the LH $K^*$ mesons at low $q^2$ is predicted. This property prompts that a study of the transverse asymmetry of $K^*$ produced in the $B \rightarrow K^* \ell^+ \ell^-$ decays can discriminate between the LR models on the one hand, and the SM and MSSM on the other. To be more rigorous, a difference of the $K^*$ transverse asymmetry from unity would be a clear and specific signal of the presence of the RH currents in the Effective Hamiltonian.

We show also that, as fas as other observables, like $A_{FB}$ and $P_L$, are concerned, the presence of the RH quark currents in the effective Hamiltonian yields generally the same type of deviations from the SM predictions as one might expect within the MSSM.

1 Effective Hamiltonians and differential distributions

The effective Hamiltonian for the $b \rightarrow s$ transition has the structure \[7\]:

$$H_{eff} = \frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i(\mu) O_i(\mu).$$

The operator bases in the SM and MSSM coincide. The operators which give the main contributions are

$$O_1 = (\bar{s}_\alpha \gamma^\mu (1 - \gamma_5) b_\alpha)(\bar{c}_\beta \gamma_\mu (1 - \gamma_5) c_\beta),$$

$$O_2 = (\bar{s}_\alpha \gamma^\mu (1 - \gamma_5) b_\alpha)(\bar{c}_\beta \gamma_\mu (1 - \gamma_5) c_\alpha),$$

$$O_{7\gamma} = \frac{e}{8\pi^2} \bar{s}_\alpha \sigma_{\mu\nu} m_b(\mu) (1 + \gamma_5) b_\alpha F^{\mu\nu},$$

$$O_{9V} = \frac{e^2}{8\pi^2} (\bar{s}_\alpha \gamma^\mu (1 - \gamma_5) b_\alpha) \bar{l}_\gamma l,$$

$$O_{10A} = \frac{e^2}{8\pi^2} (\bar{s}_\alpha \gamma^\mu (1 - \gamma_5) b_\alpha) \bar{l}_\gamma \gamma_5 l$$

(2)
and the whole difference of the models at large mass scales shows itself in the $B$-decays as the difference in the values of the Wilson coefficients at the low mass scales.

The equations for the Wilson coefficients in the SM can be found e.g. in [4]. At the scale $\mu \simeq m_b$ they take the values $C_1(m_b) = 0.241$, $C_2(m_b) = -1.1$, $C_{7\gamma}(m_b) = 0.312$, $C_{9\gamma}(m_b) = -4.21$, $C_{10A}(m_b) = 4.64$. In the MSSM, if SUSY particles have masses above 200 GeV, the $C_{9\gamma}^{MSSM}$ and $C_{10A}^{MSSM}$ differ from the corresponding coefficients in the SM by no more than 10%. So in all further estimates we can safely set $C_{9\gamma}^{MSSM} = C_{9\gamma}^{SM}$ and $C_{10A}^{MSSM} = C_{10A}^{SM}$. Fortunately, the difference in the coefficient $C_{7\gamma}$ in SM and MSSM might be much more pronounced since the $C_{7\gamma}^{MSSM}$ can take values from a broad interval for different regions of the MSSM parameter space. The experimental results on $B \to K^{*}\gamma$ and $B \to X_s\gamma$ restrict the value $R_{7\gamma}(M_W) = C_{7\gamma}^{MSSM}(M_W)/C_{7\gamma}^{SM}(M_W)$ to be in the following regions

$$-4.2 < R_{7\gamma} < -2.4, \quad 0.4 < R_{7\gamma} < 1.2.$$ (3)

In the LR models [3, 4] the set of the basis operators is wider and includes also operators with right-handed quark currents, the most important of which are

$$O_1^R = (\bar{s}_\alpha \gamma^\mu (1 + \gamma_5) b_\alpha) (\bar{c}_\beta \gamma_\mu (1 + \gamma_5) c_\beta),$$

$$O_2^R = (\bar{s}_\alpha \gamma^\mu (1 + \gamma_5) b_\alpha) (\bar{c}_\beta \gamma_\mu (1 + \gamma_5) c_\alpha),$$

$$O_{7\gamma}^R = \frac{e}{8\pi^2} \bar{s}_\alpha \sigma_{\mu\nu} m_b (\mu) (1 - \gamma_5) b_\alpha \bar{F}^{\mu\nu},$$

$$O_{9V}^R = \frac{e^2}{8\pi^2} (\bar{s}_\alpha \gamma^\mu (1 + \gamma_5) b_\alpha) \bar{l}_{\gamma\mu l},$$

$$O_{10A}^R = \frac{e^2}{8\pi^2} (\bar{s}_\alpha \gamma^\mu (1 + \gamma_5) b_\alpha) \bar{l}_{\gamma\mu\gamma_5 l}. \quad (4)$$

The result of the analysis of the Wilson coefficients in the LR models [3, 4] shows that in all possible LR model variants the values of the Wilson coefficients $C_{9V}^R$ and $C_{10A}^R$ can be neglected compared to the $C_{9V}^L$ and $C_{10A}^L$ which in turn do not deviate considerably from the corresponding SM values. So in the LR case as well as in the MSSM, only the difference in $C_{7\gamma}$ is to be taken into account.

The LR model parameter space can be described by the values of the right-handed gauge boson mass $M_{WR}$, the coupling constants of the left- and right-handed currents $g_{2L}$ and $g_{2R}$, respectively, the mixing angle $\zeta$ and the phase $\beta$ of the gauge boson mass matrix [3]. The phase $\beta$ is small [3] and can be neglected since we are not interested in the small $CP$ violation effects. The Wilson coefficients in fact depend only on the combination $\zeta_g = (g_{2R}/g_{2L}) \zeta$ [3]. Thus the low-energy effective Hamiltonian in the LR model actually depends on the values $M_{WR}$ and $\zeta_g$ and the $CKM_R$ matrix elements. To illustrate the possible impact of the right-handed currents on the observables in rare SL decays, we use one set of the $CKM_R$ parameters from [3] denoted as $V_R = V_L$ with $M_{WR} = 1.6 \, TeV$ and the range of $\zeta_g$ determined from the CLEO data on $B \to K^{*}\gamma$.

For the effective Hamiltonian [3] with the operator set given by eq. (2) and applying the method of Ref. [14] in the case of massless leptons and in the limit $m_\chi \to 0$, one finds for the differential distribution $d^4 \Gamma / dq^2 d \cos \theta_i d \cos \theta_V d \chi$ in a cascade $B \to K^{*}(\to K\pi)\ell^+\ell^-$ decay
the following general expression:

\[
\frac{d^4\Gamma(B \to K^*(\to K\pi)\ell^+\ell^-)}{dq^2d\cos\theta_d d\cos\theta_V d\chi} = \frac{3G_F^2}{8(4\pi)^4} \left( \frac{e^2}{8\pi^2} |V_{ts}V_{tb}| \right)^2 \frac{\phi^{1/2} M_B}{2 M_B^2} B r(K^* \to K\pi)
\]

\[
= \frac{1}{(4\pi)^4} \left[ (1 - \cos\theta_t)^2 \sin^2\theta_V \left( |H^t_+|^2 + |H^r_+|^2 \right) + (1 + \cos\theta_t)^2 \sin^2\theta_V \left( |H^t_-|^2 + |H^r_-|^2 \right) + 4 \sin^2\theta_t \cos^2\theta_V \left( |H^t_0|^2 + |H^r_0|^2 \right) - 2 \sin^2\theta_t \sin^2\theta_V \cos(2\chi) \left( \text{Re} \left( H^t_+ H^r_- \right) + \text{Re} \left( H^r_+ H^t_- \right) \right) \right]
\]

where \( q = p_B - p_{K^*} \), \( \phi = \lambda(1, \hat{s}, \hat{r}) = 1 + \hat{s}^2 + \hat{r}^2 - 2\hat{s} - 2\hat{r} - 2\hat{s}\hat{r}, \hat{s} = q^2/M_B^2 \) and \( \hat{r} = (M_{K^*}/M_B)^2 \).

The notation of the kinematical variables follows the conventional notation of ref. \[11\].

The representations \( H^{l,r}_{\lambda} \) (\( \lambda = 0, \pm \) is the \( K^* \) meson helicity state) have the following structure in terms of the meson transition form factors (see \[3\] for their definitions)

\[
H^l_{\lambda} = C^{l,r} f(q^2) - \frac{C_{\tau\gamma}}{s} m_b (1 - \hat{r}) B_0(q^2)
\]

\[
+ \phi^{1/2} \left( \frac{C_{\tau\gamma}}{s} M_B^2 g(q^2) - \frac{C_{\tau\gamma}}{s} m_b g_+(q^2) \right),
\]

\[
H^r_{\lambda} = -\frac{1}{2\sqrt{\hat{r}\hat{s}}} \left[ (1 - \hat{r} - \hat{s}) \left( C^{l,r} f(q^2) - \frac{C_{\tau\gamma}}{s} m_b (1 - \hat{r}) B_0(q^2) \right) \right.
\]

\[
\left. + \phi \left( \frac{C_{\tau\gamma}}{s} M_B^2 a_+(q^2) - \frac{C_{\tau\gamma}}{s} m_b B_+(q^2) \right) \right],
\]

\[
C^l = \frac{1}{2} \left( C_{9V}^{\tau\gamma} f(q^2, m_b^2) - C_{10A}(m_b) \right), \quad C^r = \frac{1}{2} \left( C_{9V}^{\tau\gamma} f(q^2, m_b^2) + C_{10A}(m_b) \right),
\]

where the superscripts \( l, r \) in \( H \) label the helicity structure of the corresponding leptonic current.

The representations \( \{5\} \) and \( \{6\} \) allow one to obtain formulas in various interesting cases making appropriate substitutions. The form of such substitutions can be readily obtained from the form of the corresponding Effective Hamiltonian, viz.

i. **SL decays, like** \( B \to D^{\ast}\ell\nu_{\ell} \), **in the SM**: the formula for the decay rate is obtained by substituting

\[
C_{\tau\gamma} \to 0, \quad \bar{C}^l \to 1, \quad \bar{C}^r \to 0, \quad \frac{e^2}{8\pi^2} |V_{ts}V_{tb}| \to |V_{bc}|.
\]

ii. **Rare decay** \( B \to K^*\nu\bar{\nu} \) **in the SM**:
iii. Rare SL decay $B \rightarrow K^*\ell^+\ell^-$ in the LR models: if we consider the case of massless leptons and neglect the $s$-quark mass, then the left- and right-handed parts of both the leptonic and the quark currents do not mix with each other and the differential decay rate in the LR model, described by the effective Hamiltonian \((1)\) with the operator set including \((2)\) and \((4)\), can be obtained by substituting

\[
C_{7\gamma} \rightarrow 0, \quad C_{9y}^{\text{eff}} \rightarrow \frac{X(x_t)}{\sin^2 \theta_W}, \quad C_{10A} \rightarrow -\frac{X(x_t)}{\sin^2 \theta_W}. \tag{8}
\]

We are interested only in the nonresonant contribution to the decay rate \((3)\), since only the nonresonant part encodes the information on the Wilson coefficients. In this case all purely imaginary terms in eq. \((5)\) can be neglected.

The differential distributions of the produced $K^*$ mesons with definite helicity takes the form

\[
\frac{d\Gamma_{\lambda}}{dq^2} = \frac{G_F^2}{96\pi^2} \left( \frac{e^2}{8\pi^2} |V_{ts}V_{tb}| \right)^2 \phi^{1/2} \frac{M_B}{2} q^2 \frac{1}{M_B^2} \left| [H_{\lambda}^1]^2 + |H_{\lambda}^2|^2 \right|. \tag{10}
\]

For the transverse asymmetry defined as

\[
A_T(q^2) = \frac{d\Gamma_-/dq^2 - d\Gamma_+/dq^2}{d\Gamma_-/dq^2 + d\Gamma_+/dq^2} \tag{11}
\]

one finds the expression

\[
A_T(q^2) = \frac{2\phi^{1/2} R_T(q^2)}{\phi |G(q^2)|^2 + |F(q^2)|^2}, \tag{12}
\]

where

\[
R_T(q^2) = \text{Re} \left[ \left( C_{9y}^{\text{eff}}(m_b, q^2) M_B g(q^2) - \frac{2C_{7\gamma}(q^2)}{\hat{s}} \frac{m_b}{M_B} g_+(q^2) \right) \right. \times \left. \left( C_{9y}^{\text{eff}}(m_b, q^2) f(q^2) M_B - \frac{2C_{7\gamma}(m_b, q^2)}{\hat{s}} \frac{m_b}{M_B} (1 - \hat{r}) B_0(q^2) \right) \right]^{*} + |C_{10A}|^2 f(q^2) g(q^2) \tag{13}
\]
The angular distribution of the $K$ mesons produced in the subsequent decay $K^* \to K\pi$ in the $K^*$ rest frame has the form

$$
\frac{d\Gamma}{d\cos\theta_V} \sim 1 + \alpha \cos^2\theta_V,
$$

with

$$
\alpha = \frac{s_{\text{max}}^{1/2} \int_{s_{\text{min}}}^{s_{\text{max}}} \tilde{s}^{1/2} \left( \left( \frac{(1-\tilde{s}^{1/2})^2}{4r} - \tilde{s} \right) |F(q^2)|^2 - \tilde{s}|G(q^2)|^2 + \frac{\tilde{s}^2}{4r} |H_+(q^2)|^2 - \frac{\tilde{s}(1+\tilde{r})}{2r} R(q^2) \right) \right) - s_{\text{min}}^{1/2} \int_{s_{\text{min}}}^{s_{\text{max}}} \tilde{s}^{1/2} \left( \tilde{s}|G(q^2)|^2 + \tilde{s}|F(q^2)|^2 \right)
$$

where $s_{\text{min}} = 4m_t^2/M_B^2$ and $s_{\text{max}} = (M_B - M_{K^*})^2/M_B^2$.

\section{Numerical analysis}

In this section we illustrate the possible specific effects which might be expected in the LR models due to the presence of the right-handed quark currents. In numerical calculations we use the form factors obtained within the GI-OGE model\cite{9}.

Notice that at large $q^2$ everything is determined by the Wilson coefficients $C_{9V}$ and $C_{10A}$ since they are much larger than $C_7$. This means that all models (SM, MSSM, LR) give more or less the same results for all observables since the deviations in $C_{9V}$ and $C_{10A}$ in all extentions of the SM are not large. On the contrary, at small $q^2$ a photon pole starts to dominate all observables and the $C_7$ effects are enhanced considerably. Since most of the new physics effects lead to deviations of $C_{7\gamma}$ from its SM value, different extentions of the SM might become distinguishable.

For an illustration of the RH currents influence, we take one of the variants of the LR model from \cite{4}, namely the extension called $V_L = V_R$. In this case the right-handed CKM matrix and $M_{W_R}$ are fixed and the freedom of the LR parameter space is reduced to the value of one parameter only, namely $\zeta_g$. The allowed range of $\zeta_g$ is constrained by the CLEO data \cite{13, 14} on rare radiative inclusive and exclusive $b \to s\gamma$ transitions

$$
Br(B \to X_s\gamma) = \frac{G_L^2\alpha_{em}^2 m_b^5}{32\pi^4} |V_{ts}^L V_{tb}^L|^2 \left( |C_{7\gamma}^L(m_b)|^2 + |C_{7\gamma}^R(m_b)|^2 \right),
$$

$$
Br(B \to K^*\gamma) = \frac{G_L^2\alpha_{em}^2}{32\pi^4} |V_{ts}^L V_{tb}^L|^2 \left( |C_{7\gamma}^L(m_b)|^2 + |C_{7\gamma}^R(m_b)|^2 \right) m_b^2 (M_B^2 - M_{K^*}^2) |g_+(0)|^2.
$$

One finds the allowed region to be

$$
-0.02 \leq \zeta_g \leq 0.002.
$$

Fig. 1 shows the $A_{FB}$ and $P_L$ in the LR model. In the region of small $q^2$ the forward-backward asymmetry $A_{FB}$ and the lepton polarization asymmetry $P_L$ in MSSM and LR model might
be different from the SM but the presence of the right-handed quark currents does not add any specific effects and one might expect in most favorable case $\zeta_g \simeq -0.02$ the same type of deviations from the SM within MSSM and LR models.

The angular distribution of the secondary $K$ in the cascade decay $B \to K^* \ell^+ \ell^- \to K\pi\ell^+ \ell^-$ in the $K^*$ rest frame (see eq. (14)) turns out to be sensitive to the Wilson coefficients, as it is illustrated in Table 1. However, the character of the deviations from the SM is similar within the LR and MSSM. So $A_{FB}, P_L$, and the angular distribution of secondary $K$ mesons can probe the extentions of the SM, but they are not sensitive to the specific structure of such extentions.

Table 1: Parameter of the angular distribution of the secondary $K$ produced in $B \to K^* \ell^+ \ell^- \to K\pi\ell^+ \ell^-$. When calculating $\alpha$ the regions of the resonances have been excluded.

|        | SM       | MSSM     | LR        |
|--------|----------|----------|-----------|
| $R_{7\gamma}$ | $1$      | $-4.2 \div -2.4$ | $0.4 \div 1.2$ | $\zeta_g = -0.02 \div 0.002$ |
| $\alpha$  | $1.64$   | $0.45 \div 1.3$ | $1.6 \div 2.0$ | $0.7 \div 1.8$ |

One might expect that the helicity structure of the Effective Hamiltonian can affect the helicity distributions of the final $K^*$ mesons. In fact, the distributions of the produced $K^*$ in definite helicity states can be considerably affected. Fig. 2 shows the distributions of the right-handed (a) and the left-handed (b) $K^*$. One can see that the yield of the right-handed $K^*$ in the region of small $q^2$ might be remarkably increased in the LR models (see also [6]). Such an increase of the right-handed $K^*$ mesons in comparison with the predictions of models having suppressed RH quark currents, like the SM or the MSSM, can provide a very specific behavior of the transverse asymmetry $A_T(q^2)$, as it is shown clearly in Fig. 3. Thus we may conclude that any sizeable difference of $A_T(q^2)$ from unity in the region of small $q^2$ would signal the presence of the RH quark currents.

Notice that the results presented are not affected significantly by the uncertainties in the meson transition form factors: the asymmetries are weakly sensitive to the subtle details of the form factor behavior (see the discussion in [7]) and the right-handed $K^*$ enhancement in the LR models far overwhelmes the uncertainties due to the model dependence of the form factors. Hence an experimental study of the transversely polarized $K^*$ mesons in rare $B \to K^* \ell^+ \ell^-$ decays might shed light on the possible presence of the RH quark currents and their strength.

Acknowledgments. The authors are grateful to T. Rizzo for helpful comments on the LR models.
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Figure 1: Forward-backward asymmetry $A_{FB}$ and longitudinal lepton polarization asymmetry $P_L$ in $B \rightarrow K^* \ell^+ \ell^-$ decays: solid - SM result, dotted - LR model result ($V_L = V_R$ parameter set), lower and upper lines correspond to $\zeta_g = -0.02$ and $\zeta_g = 0.002$, respectively, dashed line - MSSM with $R_{7\gamma} = -2.4$. The values of $P_L$ in the SM and in the LR model with $\zeta_g = 0.002$ practically coincide and are not distinguishable in the figure.

Figure 2: Helicity distributions of $K^*$ produced in $B \rightarrow K^* \ell^+ \ell^-$ decays: (a) $d\Gamma_+/dq^2$, (b) $d\Gamma_-/dq^2$: solid - SM result, dotted - LR model result ($V_L = V_R$ parameter set) corresponding to $\zeta_g = -0.02$, dashed line - MSSM with $R_{7\gamma} = -2.4$. 

Figure 3: Differential transverse asymmetry $A_T(q^2)$ of $K^*$ mesons produced in $B \to K^*\ell^+\ell^-$ decays: solid - SM result, dotted - LR model result ($V_L = V_R$ parameter set) corresponding to $\zeta_\phi = -0.02$, dashed line - MSSM with $R_{7\gamma} = -2.4$. 