# Short distance coefficients and the vanishing of the lepton asymmetry in $B \rightarrow Vl^+l^-$

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We derive a condition the short distance coefficients governing $b \rightarrow (s,d)\ell^+\ell^-$ transitions must satisfy in order for the forward-backward asymmetry to vanish in the exclusive modes $B \rightarrow (K^*,\rho)\ell^+\ell^-$. This relation, which is satisfied in the standard model, involves the coefficient entering in $b \rightarrow s\gamma$ transitions as well as one of the additional Wilson coefficients present in the leptonic modes. We show that the resulting relation is largely free of hadronic uncertainties, thus constituting a reliable test of the standard model in exclusive rare $B$ decays. [S0556-2821(98)00409-3]

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Transitions involving flavor changing neutral currents (FCNCs) have attracted a great deal of interest given that they are forbidden at tree level in the standard model (SM). This suggests that they have a great potential as tests of the SM as well as to bound its extensions. This is particularly true of decays governed by the transitions $b \rightarrow q\gamma$, $b \rightarrow q\ell^+\ell^-$ ($q=s,d$) and similar other FCNC decays of the $b$ quark. It is generally believed that this potential is mostly realized in inclusive decays, given that these are theoretically under control. However, these tend to present more experimental difficulties [1]. On the other hand, the predictions for exclusive decay modes are affected by large theoretical uncertainties originating in the hadronic matrix elements. A great deal of progress in lattice calculations has been achieved in recent years [2]. However, uncertainties remain important for large recoil momenta. This situation makes it, *a priori*, difficult to extract short distance information from the experimental observations of these decays. This is certainly the case for $B \rightarrow K^*\gamma$. Although this also applies to the predictions of the hadronic matrix elements in the $b \rightarrow q\ell^+\ell^-$ modes, the combination of symmetries with other experimental observations can drastically reduce the theoretical uncertainties in some decay modes. Such is the case for the decay $B \rightarrow V\ell^+\ell^-$ ($V=K^*,\rho$), for which the form factors can be predicted using a combination of heavy quark spin symmetry (HQSS), isospin symmetry [SU(3) for $V=K^*$] and the form factors to be measured in $B \rightarrow \rho\ell\nu$ [3,4]. Thus, relatively safe predictions can be made for the decay rate, as well for the forward-backward asymmetry of leptons as a function of the dilepton mass, $A_{FB}(m_{\ell\ell})$. The latter has been shown to be very sensitive to extensions of the SM [4]. This is, of course, also the case in inclusive decays, where the hadronic uncertainties are smaller. The potential of $A_{FB}$ as a test of the SM in inclusive decays has been studied at length in the literature [5].

In the SM, $A_{FB}(s)$ vanishes for a certain value of $s$. This is the case in inclusive decays as well as in the exclusive modes $B \rightarrow V\ell^+\ell^-$. In the inclusive modes [6], the value of the dilepton mass for which the asymmetry vanishes depends on two of the three short distance Wilson coefficients determining the transition. On the other hand, in exclusive modes, the location of the zero depends also on hadronic form factors. In this paper we will show that the determination of the dilepton mass $s_0$ for which $A_{FB}(s)$ vanishes constitutes a stringent test of the SM even in the exclusive decay modes. We will derive the relation among the short distance Wilson coefficients governing the $b \rightarrow q\ell^+\ell^-$ transitions, that results from the vanishing condition for $A_{FB}(s)$, and show that this condition is not affected by large theoretical uncertainties in exclusive channels.

The separation of short and long distance physics takes place in the operator product expansion of the effective Hamiltonian. This is given by

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}^* V_{tq} \sum_i C_i(\mu) O(\mu), \tag{1}$$

where the operator basis $\{O_i\}$ is defined in [7], $\mu$ is a renormalization scale and the Wilson coefficient functions $C_i(\mu)$ are determined by the short distance structure of the underlying physics. To compute the amplitude for the exclusive modes we will need the hadronic matrix elements of the operators $O_i$. The $B \rightarrow K^*\ell^+\ell^-$ mode dominates in the SM due to the CKM suppression of the $\rho$ mode. The main results of this paper are generally valid for any vector meson $V$. The Lorentz structure of the operators defines various form factors. The matrix elements necessary to describe this decay are

$$\begin{aligned}\langle V(\mathbf{k},\epsilon)|\overline{s}_L\gamma_\mu b_L|B(\mathbf{p})\rangle = \frac{1}{2}\{ & ig\epsilon_{\mu\nu\alpha\beta}\epsilon^{*\nu}(p+k)^\alpha(p-k)^\beta \\ & - f\epsilon_\mu^* - a_+(\epsilon^*\cdot p)(p+k)_\mu \\ & - a_-(\epsilon^*\cdot p)(p-k)_\mu\},\end{aligned} \tag{2}$$

and

$$\begin{aligned}\langle V(\mathbf{k},\epsilon)|\overline{s}_L\sigma_{\mu\nu}b_L|B(\mathbf{p})\rangle = & \frac{1}{2}\epsilon_{\mu\nu\alpha\beta}\{A\epsilon^{*\alpha}p^\beta + B\epsilon^{*\alpha}k^\beta \\ & + C(\epsilon\cdot p)p^\alpha k^\beta\} + \frac{i}{2}\{A(\epsilon^{*\mu}p^\nu \\ & - \epsilon^{*\nu}p^\mu) + B(\epsilon^{*\mu}k^\nu - \epsilon^{*\nu}k^\mu) \\ & + C(\epsilon^*\cdot p)(p^\mu k^\nu - p^\nu k^\mu)\}.\end{aligned} \tag{3}$$

In Eqs. (2) and (3) the form factors $g$, $f$, $a_\pm$, $A$, $B$ and $C$ are

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unknown functions of the dilepton mass squared $s$. In order to compute these, one needs to model the hadron dynamics involved in the $B\to V$ transition, introducing a large theoretical uncertainty. This obscures the extraction of the interesting short distance information, encoded in the Wilson coefficients corresponding to the operators $O_7$, $O_9$ and $O_{10}$, which are the relevant ones in $b\to q\ell^+\ell^-$ transitions.

The forward-backward asymmetry for leptons as a function of the dilepton mass squared is defined as

$$A_{FB}(s)=\frac{\int_0^1 \frac{d^2\Gamma}{dxds}dx-\int_{-1}^0 \frac{d^2\Gamma}{dxds}dx}{\frac{d\Gamma}{ds}}, \tag{4}$$

where $x=\cos\theta$ and $\theta$ is the angle between the $\ell^+$ and the decaying $B$ meson in the $\ell^+\ell^-$ rest frame. It is straightforward to show that the numerator of $A_{FB}(s)$ takes the form

$$A_{FB}(s)\sim 4m_B k C_{10}\left\{\overline{C_9}gf+\frac{m_b}{s}\overline{C_7}(fG-gF)\right\}, \tag{5}$$

where $k$ is the $V$ three-momentum in the $B$ rest frame, and we have defined

$$F=Ap\cdot q+Bk\cdot q,$$

$$G=-\frac{(A+B)}{2}. \tag{6}$$

In Eq. (5) $\overline{C_7}=C_7^{\rm eff}(m_b)$ and $\overline{C_9}=C_9^{\rm eff}(m_b)$ are the effective Wilson coefficients at the scale $m_b$. These include all the effects of the renormalization group running as well as, in the case of $\overline{C_9}$, the long distance effects [9] associated with off-shell $c\bar{c}$ intermediate states.[1] Thus, $A_{FB}(s)$ vanishes for a value of $s$ determined only by two of the three Wilson coefficients, $\overline{C_7}$ and $\overline{C_9}$. This condition can be written as the relation

$$\overline{C_9}=-\frac{m_b}{s_0}\overline{C_7}\left(\frac{G}{g}-\frac{F}{f}\right), \tag{7}$$

where $s_0$ corresponds to the dilepton mass for which $A_{FB}(s)=0$ is satisfied, and the form-factors are evaluated at $s_0$. The condition (7) for the vanishing of $A_{FB}(s)$ constitutes a potentially powerful test of the SM given that it relates the Wilson coefficient governing $b\to s\gamma$ decays, $\overline{C_7}$, to one of the additional coefficients appearing in the leptonic modes, the one that determines the vector coupling to the lepton current. However, and as it is frequently the case for exclusive decay modes, large theoretical uncertainties are present in (7), a result of our inability to compute the form-factors $F(s)$, $G(s)$, $f(s)$ and $g(s)$ within a controlled approximation. In what follows we show that, with the use of well established symmetry arguments, it is possible to derive from (7) a relation between $\overline{C_7}$ and $\overline{C_9}$ that is largely free of the hadronic theoretical uncertainties mentioned above.

In the limit $m_b\gg\Lambda$, with $\Lambda$ the typical scale of the strong interactions inside the $B$ meson, the spin of the $b$ quark decouples from the light degrees of freedom [8]. This results in various relations among hadronic matrix elements and, therefore, among the form factors parametrizing them. We will refer to these as heavy quark spin symmetry (HQSS) relations. The HQSS relations corresponding to the matrix elements of (2) and (3) allow us to express the form factors $F$ and $G$ as functions of the "semileptonic" form factors $f$ and $g$ [10]. They take the form

$$F=-f(m_B-E_V)-2m_Bg(m_BE_V+k^2), \tag{8}$$

$$G=\frac{f+2m_B(m_B-E_V)g}{2m_B}, \tag{9}$$

where $E_V$ and $k$ are the energy and momentum of the $V$ meson in the $B$ rest frame, respectively. Furthermore, the form factors $f$ and $g$ entering in the $(V-A)$ $B\to V$ matrix element (2), can be identified with the analogous form factors entering in the semileptonic decay $B\to\rho\ell\nu$. In the case $V=\rho$ this identification only makes use of isospin symmetry, whereas for $V=K^*$ the use of SU(3) symmetry is required. We address the issue of SU(3) corrections later in the paper. We can then rewrite the condition (7) making use of (8) and (9), which gives

$$\overline{C_9}=-\frac{m_b}{2s_0}\overline{C_7}\left\{4m_Bk^2R_V+\frac{1}{m_BR_V}+4(m_B-E_V)\right\}, \tag{10}$$

where we defined the ratio

$$R_V\equiv\frac{g(s_0)}{f(s_0)}, \tag{11}$$

and all quantities depending on the dilepton mass must be evaluated at $s=s_0$. This is the main result of the paper. The relation (10) between $\overline{C_7}$ and $\overline{C_9}$ now only depends on the ratio of the vector to axial-vector form factors $R_V$, which in turn can be experimentally extracted from the decay $B\to\rho\ell\nu$.

Corrections to (10) are expected to be small. The HQSS relations (8) and (9) receive corrections suppressed by inverse powers of the $b$ quark mass. These come from the fact that the HQSS neglects the lower components of the $b$-quark spinor. Thus, the suppressed terms are proportional to $p_b/m_b$, where $p_b$ is the $b$ quark momentum in the $B$ meson rest frame and is of the order of the typical momentum exchanged with the light degrees of freedom, $\Lambda$. Thus, we expect the typical size of these corrections to be of the order of 10% or less.

Up to this point we have not specified the vector meson in the final state. In the SM, the branching ratio for the $K^*$ mode is expected to be about a factor of 20 larger than the one for the $\rho$ mode, due to the ratio of Cabibbo-Kobayashi-Maskawa (CKM) matrix elements $V_{ts}/V_{td}$. For the $B\to K^*\ell^+\ell^-$ decay is important to address the corrections to the SU(3) identification of the form factors $f$ and $g$ with those entering in the semileptonic decay $B\to\rho\ell\nu$. Estimates

[1]It is assumed that the resonant $J/\psi$ and $\psi'$ contributions are explicitly removed. Various treatments of the long distance contributions exist. The associated uncertainty, however, has very little effect well below the $J/\psi$, where $s_0$ is likely to be.

of these corrections in specific calculations indicate they are small as long as the recoil energy of the $K^*$ is large enough. To show this explicitly we can make use of some general properties of the constituent quark model picture that are likely to capture the correct SU(3) breaking effects. This is the situation if one uses the formalism proposed by Stech [11] and further developed by Soares [12] to include light quark mass effects, which is fully relativistic and incorporates correctly the quark spin degrees of freedom. The spin structure plays a fundamental role in the ratios of form factors. We are interested in estimating the double ratio

$$\delta \equiv \frac{R_V^{K^*}}{R_V^{\rho}}, \tag{12}$$

where $R_V^{K^*}$ refers to the quantity in (10), whereas $R_V^{\rho}$ corresponds to the quantity extracted from $B \to \rho \ell \nu$. The deviations from $\delta = 1$ are a measure of the amount of SU(3) breaking. Within the formalism of [11,12] we obtain the approximate expression

$$\delta \simeq \frac{1 + m_d/(E_{K^*} - E_{\rm sp})}{1 + m_s/(E_{K^*} - E_{\rm sp})}, \tag{13}$$

where $m_d$ and $m_s$ are the down and strange quark constituent masses, and $E_{\rm sp}$ is the energy of the spectator quark inside the vector meson. This is typically of the order of $\Lambda$, i.e. a few hundred MeV. Thus, for large enough values of $E_{K^*}$, the ratio $R_V$ is not very sensitive to SU(3) breaking effects. For instance, for the typical values $m_d = E_{\rm sp} = 300$ MeV, $m_s = 450$ MeV, the SU(3) breaking effect is below 15% for $E_{K^*} > 1$ GeV. As we will see below, the typical recoil energies where the asymmetry vanishes are even larger.

The measurement of the ratio $R_V$ from $B \to \rho \ell \nu$ decays will hopefully be available in the $B$ factory era. Thus, the measurement of $s_0$ in any of the $B \to V \ell^+ \ell^-$ modes can be turned into a test of the SM via the relation (10). However, it is interesting to estimate the value of $s_0$ in the SM, in order to see that it typically corresponds to a region with large recoil energy $E_V$. In order to illustrate this point we can use again Stech's formalism. Then the ratio of vector to axial-vector form factors is simply

$$R_V \simeq -\frac{1}{2 m_B k}. \tag{14}$$

Now the condition (10) for the vanishing of the asymmetry simplifies to

$$\overline{C}_9 \simeq -2 \frac{m_b}{s_0} \overline{C}_7 (m_B - E_V - k), \tag{15}$$

which, solving for $s_0$, translates into

$$s_0 \simeq \frac{m_B^2 + m_V^2 (2\overline{C}_7/\overline{C}_9 - 1)}{1 - \overline{C}_9/2\overline{C}_7}. \tag{16}$$

We can use this expression to obtain an estimate of $s_0$ in the SM. For instance, using the next-to-leading order value for $\overline{C}_7$ [13] and the corresponding value of $\overline{C}_9$ as described in [14] one obtains, for $V = K^*$, $s_0 \simeq 3.9$ GeV$^2$. This value is in

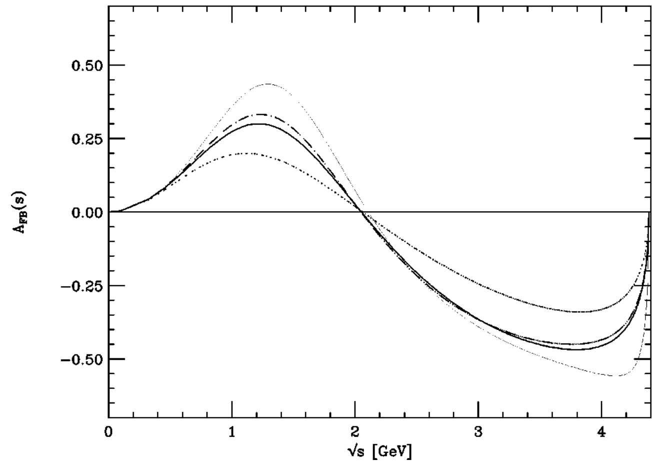


FIG. 1. The non-resonant forward-backward asymmetry of leptons $A_{FB}$ defined in (4), for $B \to K^* e^+ e^-$ as a function of the dilepton mass $s$. The asymmetry is computed by making use of the relations (8) and (9) and the semileptonic form factors from: the BSW* model of [15] (solid line), the light-cone QCD sum rule calculation of [16] (dashed line) and the relativistic quark model of [17] (dotted line). The lighter solid line corresponds to the BSW* model with the vector form factor $g$ multiplied by a factor of two, and illustrates the uncertainty in the position of the $A_{FB}$ zero.

remarkable agreement with what is obtained with typical model calculations of $R_V$. This is not entirely surprising since, although Stech's formalism makes use of the constituent quark picture, the ratio $R_V$ is independent of wave functions and overlap integrals, which typically are the main source of disagreement among different calculations of individual form factors. In Fig. 1 we illustrate this point by plotting the non-resonant forward-backward asymmetry $A_{FB}(s)$ defined in (4) as a function of the dilepton mass $s$, for the model calculations of [15,16,17]. The location of the zero of the lepton asymmetry is fully determined by $R_V$. This ratio tends to be very similar across models, even when the values of the individual form factors may differ. Also shown, is the result of one of the models (BSW*) obtained by significantly changing $R_V$ by doubling the value of the vector form factor $g$. The resulting shift in the position of the asymmetry zero gives a conservative estimate of the theoretical uncertainty one incurs in by using models. On the other hand, such shift in $R_V$ would significantly affect the $B \to \rho \ell \nu$ branching ratio, enhancing it by a factor of $(2-3)$ depending on the $s$ dependence. Such dramatic effects, already bound by the present CLEO measurement of this mode [18], will be extremely constrained by more precise measurements in the $B$-factory era. Thus, we conclude that the value of $s_0$ is much less sensitive to changes in $R_V$ than $B \to \rho \ell \nu$. In this way, we see that high precision in the extraction of $R_V$ *is not a necessary condition* in order to have a precise prediction of the position of the zero in the asymmetry $A_{FB}(s)$.

Extensions of the SM modify the matching conditions of the short distance coefficients [3,19], therefore potentially upsetting the relation (10). A change in $\overline{C}_7$ and/or $\overline{C}_9$ would appear as a shift in $s_0$. On the other hand, a new contribution mainly affecting $C_{10}$ would have no effect on the zero of $A_{FB}(s)$, whereas it would affect other quantities such as momentum distributions, branching ratios, etc. Such is the discriminating power of measuring the location of the $A_{FB}(s)$

zero. For instance, since the sign of $\overline{C}_7$ is not measured in $b \to s\gamma$, it is in principle possible that it is the opposite to the SM prediction. In this extreme case, the forward-backward asymmetry does not have a zero in the physical region. Less drastic modifications occur in several scenarios involving new states which contribute to the one-loop $b \to q\ell^+\ell^-$ transition amplitude.

The current experimental limits [20] on $b \to q\ell^+\ell^-$ processes, although still above the SM expectations, indicate that sensitivity to these transitions will be achieved soon and that, in some cases, large data samples could be accumulated in the near future. We have shown that it is possible to reliably test the SM in exclusive FCNC $B$ decays. In particular, we have seen that the measurement of the zero of the forward-backward asymmetry for leptons, $A_{FB}(s)$, in $B \to V\ell^+\ell^-$ decays provides a test of the short distance structure of the SM and its extensions, within a controlled approximation. The relation (10) involving the Wilson coefficients $\overline{C}_7$ and $\overline{C}_9$ is derived by making use of the heavy quark spin symmetry, and is expected to receive only small corrections. These are the same corrections leading to $(m_{B*}-m_B)/m_B \simeq 0.009$. The experimental measurement of the ratio of form factors $R_V$ from $B \to \rho\ell\nu$ decays, even if not a very precise one, together with the condition (10), provides a stringent test of the SM in the CKM-suppressed mode $B \to \rho\ell^+\ell^-$. The CKM-favored mode $B \to K^*\ell^+\ell^-$ requires the use of SU(3) symmetry relations among the form factors. We estimated the SU(3) breaking corrections in (13) to be small for a fast recoiling $K^*$. On the other hand, we have also estimated the approximate value of the dilepton mass $s_0$ for which $A_{FB}$ vanishes and found it to be typically at a lepton mass corresponding to $E_{K*} \simeq 2.3$ GeV which, according to (13), would imply a very small SU(3) correction of the order of 6%. Thus this exclusive mode, which is experimentally favored over other exclusive channels as well as over the inclusive decay, provides a test of the short distance structure of flavor changing neutral currents.

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