Enhanced electroweak penguin amplitude in $B \to VV$ decays

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We discuss a novel electromagnetic penguin contribution to the transverse helicity amplitudes in $B$ decays to two vector mesons, which is enhanced by two powers of $m_b/\Lambda$ relative to the standard penguin amplitudes. This leads to unique polarization signatures in penguin-dominated decay modes such as $B \to \rho K^*$ similar to polarization effects in the radiative decay $B \to K^*\gamma$, and offers new opportunities to probe the magnitude and chirality of flavour-changing neutral current couplings to photons.

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INTRODUCTION

Decays of $B$ mesons into two charmless mesons provide an abundant source of information on flavour- and CP-violating phenomena in the weak interactions of quarks. In particular, decays to two vector mesons ($B \to VV$) can shed light on the helicity structure of these interactions through polarization studies. While predicted to be fundamentally V-A in the Standard Model (SM), a deviation from this expectation cannot currently be excluded. The first observations of $B \to VV$ decays show no anomalies in the helicity structure, but point to a reduced amount of longitudinal polarization in penguin-dominated decays [1]. This has led to theoretical studies that reconsider strong interactions effects in $B \to VV$ decays [2-4], or invoke new fundamental interactions [5].

Any particular $B \to VV$ decay is characterized by the three helicity amplitudes $A_0$ (longitudinal), $A_-$, and $A_+$. A quark model or naive factorization analysis [6] leads to the expectation that for $B$, i.e. $b$-quark, decay the helicity amplitudes are in proportions

\[ A_0 : A_- : A_+ = 1 : \frac{\Lambda}{m_b} : \left( \frac{\Lambda}{m_b} \right)^2 \]

with $\Lambda \approx 0.5$ GeV the strong interaction scale and $m_b \approx 5$ GeV the bottom quark mass. This expectation has been parametrically (not necessarily numerically) confirmed [2] in the framework of QCD factorization, which provides a theoretical basis for the heavy-quark expansion of $B$ decays to charmless mesons [7]. The hierarchy (1) of helicity amplitudes follows from the V-A structure of the standard weak interactions.

In this Letter we point out and discuss an effect which has been neglected in all previous studies of $B \to VV$, but which substantially alters the prediction for polarization observables. The effect is connected with electromagnetic penguin transitions, and appears only for neutral vector mesons. It leads to the unique feature that the transverse electroweak penguin amplitude is dominated by the electromagnetic dipole operator providing a signature similar to polarization in radiative decays $B \to K^*\gamma$ [8], but which is easier to access experimentally.

The effect in question is related to the two diagrams shown in Figure 1. When the vector meson $V_2$ is transversely polarized, there exists a large contribution to the decay amplitude due to the small virtuality $m_{\gamma}^2$ of the intermediate photon propagator. This is in contrast to the case of longitudinal polarization, where the photon propagator is canceled, and the amplitude is local on the scale $m_b$ [9]. The large transverse amplitude is best described by a short-distance transition $b \to D\gamma$ ($D = d, s$), followed by the transition of the low-virtuality photon ($q^2 \ll m_b^2$) to the neutral vector meson. We shall perform a factorization analysis of the amplitude below.

The calculation of the diagrams in Figure 1 is straightforward. The weak interactions are given in terms of the standard effective Hamiltonian [10]. We use the conventions of [11], but generalize the electromagnetic dipole operators to include both chiralities

\[ \mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \sum_{p=u,c} \lambda_7^{(D)} \sum_{a=-,+} C_{7\gamma}^a Q_{7\gamma}^a + \ldots, \]

\[ Q_{7\gamma}^+ = -\frac{e\bar{m}_b}{8\pi^2} \bar{D} \sigma_{\mu\nu}(1 \pm \gamma_5) F^{\mu\nu}, \]

where $\lambda_7^{(D)} = V_{pb} V_{pd}^*$. The ellipses denote other operators (see [11]). In the SM $C_{7\gamma}^b$ is suppressed by a factor $m_D/m_b$, hence $Q_{7\gamma}^+$ is usually neglected. The remaining term is then simply denoted by $C_{7\gamma} Q_{7\gamma}$. However, in generic extensions of the SM, there is no reason to expect

\[ \Delta a_{5,\text{KW}}^{\rho\pi}(V_1 V_2) \]

FIG. 1: Leading contributions to $\Delta a_{5,\text{KW}}^{\rho\pi}(V_1 V_2)$ defined in the text.
a suppression of additional contributions to $\Delta T_{3,\gamma}$ relative to $C^\gamma_{\gamma}$. The coupling of the photon to the quark electric charge in $V_2$ implies that the diagrams of Figure 1 contribute to the electroweak penguin amplitude in the general flavour decomposition of hadronic two-body decay amplitudes. Adopting the $\alpha_s$ notation of [9] extended to allow for the three helicity amplitudes of $B \to VV$, the new contribution to the transverse electroweak penguin amplitudes is

$$
\Delta \alpha_{3,EW}^T(V_1 V_2) = \mp \frac{2 \alpha_{em}}{3 \pi} C_{7\gamma,\text{eff}}^T R_\mp \frac{m_B m_b}{m^2_{V_2}} \tag{4}
$$

with $C_{7\gamma,\text{eff}}^T$ taking into account the effect of quark loop diagrams (see Figure 1). $R_\mp$ is a ratio of tensor to (axial) vector $B \to V_1$ form factors such that $R_-$ equals 1 in the heavy quark limit [12], while $R_+$ is of order $m_b/\Lambda$. We note the large enhancement factor $m_B m_b/m^2_{V_2} \sim (m_b/\Lambda)^2$, which implies that the first hierarchy in (1) is inverted, rendering the negative-helicity amplitude $A_-$ leading over the longitudinal amplitude $A_0$ in the heavy-quark limit. Of course, for real values of $m_b/m_{V_2}$ this enhancement is compensated by the small electromagnetic coupling $\alpha_{em} = e^2/(4\pi)$. For instance, for neutral $\rho$ mesons, we obtain $\Delta \alpha_{3,EW}^T(K^\ast \rho) \approx 0.02$. This should be compared to the uncorrected negative-helicity electroweak penguin amplitude

$$
\alpha_{3,EW}^N(K^\ast \rho) = C_7 + C_9 + \frac{C_8 + C_{10}}{N_c} + \ldots \approx -0.01, \tag{5}
$$

and the leading QCD penguin amplitude

$$
\hat{\alpha}_4^N(\rho K^\ast) = C_4 + \frac{C_5}{N_c} + \ldots \approx -0.055. \tag{6}
$$

The $C_i$ are Wilson coefficients for the various penguin operators in the effective Hamiltonian [10], and the ellipses denote the 1-loop corrections in QCD factorization [4], which we have taken into account in the numerical estimates. In the SM the corresponding positive-helicity amplitudes are suppressed by about an order of magnitude relative to the negative-helicity ones as explained above.

There are strong-interaction corrections to the leading-order expression (4) from gluon exchange between the quark lines in the second diagram of Figure 1, and also through hard interactions with the spectator quark (not shown in the Figure) in the $B$ meson. Due to factorization as discussed below, these corrections modify only the effective $b \to D\gamma$ transition at leading order in the expansion in $\Lambda/m_b$. They have been computed in next-to-leading order in the context of factorization of exclusive radiative $B$ decays [13], and can be incorporated by substituting $C_{7\gamma}^- \to C_7^\prime$ (first paper of [13], eq. (62)). Turning this argument around, the absolute value of $\Delta \alpha_{3,EW}^T(K^\ast V_2)$ can be obtained from the branching fraction of $B \to K^\ast\gamma$ via

$$
|\Delta \alpha_{3,EW}^T(K^\ast V_2)| = \frac{2 \alpha_{em}}{3 \pi} R_\mp \frac{m_B^2}{m^2_{V_2}} \times \left( \frac{\Gamma(B \to K^\ast \gamma)}{G_F^2 |V_{tb} V_{tb}^\ast|^2 \alpha_{em} / 4 \pi} \frac{m^2_B}{m^2_B} T^K(0)^2 \right)^{1/2}, \tag{7}
$$

with $T^K(0) \approx 0.28$ a tensor form factor. This results in $|\Delta \alpha_{3,EW}^T(K^\ast \rho)| \approx 0.023$, close to the leading-order estimate from (4).

We therefore conclude that the new radiative contribution to the negative-helicity electroweak penguin amplitude is at least twice as large (and opposite in sign) as was previously assumed. For penguin-dominated $b \to s$ transitions it is almost half the size of the leading QCD penguin amplitude, and should therefore have visible impact on polarization measurements. In case of new interactions generating $C_{7\gamma}^\gamma$, the corresponding contribution to the positive-helicity amplitude (4) should be observed against a very small Standard Model background.

**FACTORIZATION ANALYSIS**

Since the existence of an amplitude violating the power counting (1) may appear surprising, we sketch how this amplitude emerges and factorizes in soft-collinear effective theory (SCET) [14]. The notation and method of the following discussion is similar to the one in [15]. After integrating out the scale $m_b$, SCET formalizes the interaction of the static $b$-quark field $h_b$ with collinear fields for the light-like direction $n_-$, in which meson $V_1$ moves, and collinear fields for the light-like direction $n_+$ of meson $V_2$. Let $\chi$ denote the collinear quark field corresponding to $V_2$, and let $V_2$ be the meson that does not pick up the spectator quark from the $B$ meson. The leading quark bilinears that have non-vanishing overlap with $\langle V_2 \rangle$ are

$$
\bar{\chi} \not\! p_\perp (1 \mp \gamma_5) \chi, \quad \bar{\chi} \not\! p_\perp \gamma'_\mu (1 \pm \gamma_5) \chi. \tag{8}
$$

The subscript $\perp$ denotes projection of a Lorentz vector on the plane transverse to the two light-cone vectors $n_\perp$. Both operators scale as $\lambda^4$ according to the SCET scaling rules; the first overlaps only with the longitudinal polarization state of $V_2$, the second only with a transverse vector meson. However, the second operator is not generated by the V-A interactions of the SM (at least at the tree and 1-loop level). This implies the power suppression of $A_\perp$ relative to $A_0$ in (1), since the leading contribution to transverse polarization now involves an operator with an additional derivative $D_\perp \sim \lambda^2 / \Lambda/m_b$.

This reasoning ignores electromagnetic effects. Including QED in SCET, there is a collinear photon field with unsuppressed interactions with collinear quarks (of the
The B \to \rho K^* System

We now focus on the eight $B \to \rho K^*$ decay modes, where the electroweak penguin amplitude is largest relative to the leading QCD penguin amplitude ($a_\rho = 3/2$). Assuming isospin symmetry, the $\rho K^*$ system is described by six complex strong interaction parameters for each helicity $h = 0, -, +$. Neglecting the colour-suppressed electroweak penguin amplitude and the doubly CKM suppressed QCD penguin amplitude is a good approximation for elucidating the effect of the new (colour-allowed) electroweak penguin contribution, hence we write

$$A_h(\rho^- K^{*0}) = P_h$$
$$\sqrt{2} A_h(\rho^0 K^{*-}) = [P_h + P_h^{EW}] + e^{-i\gamma} [T_h + C_h]$$
$$A_h(\rho^+ K^{*-}) = P_h + e^{-i\gamma} T_h$$
$$-\sqrt{2} A_h(\rho^0 K^{*0}) = [P_h - P_h^{EW}] + e^{-i\gamma} [-C_h],$$

and define $x_h = X_h/P_h$, where $P_h$ is the QCD penguin amplitude. The tree amplitudes $T_h$, $C_h$ are suppressed by the CKM factor $\epsilon_K = |V_{ub} V_{cb}^*/|V_{us} V_{cs}^*| \sim 0.025$. Assuming $\gamma = 70^\circ$ is known, one can obtain $P_h$ from an angular analysis of the $\rho^- K^{*0}$ final state, $t_h$ from $\rho^+ K^{*-}$, and $p_h^{EW}$ and $c_h$ from the remaining four decay modes. In principle, this allows for a determination of $P_h^{EW}$, which can be compared to the theoretical result. In practice, a complete amplitude analysis will be experimentally difficult.

The sensitivity to the electroweak penguin amplitude is made apparent in CP-averaged helicity-decay rate ratios such as

$$S_h \equiv \frac{2 \frac{2 \Gamma_h(\rho^0 K^{*0})}{\Gamma_h(\rho^- K^{*0})}}{|1 - p_h^{EW}|^2 + \Delta_h}$$

where $\Delta_h$ depends on $c_h$ (and mildly on $p_h^{EW}$), and vanishes for $c_h \to 0$. To estimate $S_h$, we assume that the positive-helicity amplitudes are negligible as predicted in the SM, and use the observed $\rho^- K^{*0}$ branching fraction and longitudinal polarization fraction $f_L$ to determine the magnitude of $P_0$ and $P_-$. We shall also assume that the phase of $p_h^{EW}$ is not more than 30$^\circ$ away from 0 or $\pi$. Writing $p_h^{EW} = [P_h^{EW}/T_h] \times t_h$, this amounts to the assumption that no large CP asymmetries will be found in $B \to \rho^\pm K^{*\mp}$. For all other quantities we perform a calculation in the QCD factorization framework. In this procedure there is a considerable uncertainty in $P_-$ due to the discrepant experimental results on $f_L(\rho^+ K^{*0})$ [1], which may result in an over-estimate of $P_-$. And hence an under-estimate of $p_h^{EW}$. It is therefore not excluded that the electromagnetic penguin effect is more pronounced than in the following theoretical estimates. Keeping this in mind, we find $\text{Re}(p_h^{EW}) = -0.23 \pm 0.08 [+0.14_{-0.05}]$ and $\Delta_- = -0.0 \pm 0.2$, yielding

$$S_- = 1.5 \pm 0.2 [0.7 \pm 0.1].$$
Here (and below) the numbers in brackets refer to the calculation without the new electromagnetic penguin contribution. Despite the current large theoretical uncertainties, which could be removed with more experimental data, eq. (14) clearly shows the impact of this contribution on polarization observables. The effect is even more significant for the ratio of the two final states with neutral $\rho$ mesons, as $S_{-}/S_{-}^{\prime}$ (eq. [15] below) changes by a factor of about 4 whether or not the electromagnetic penguin contribution is included, but for this ratio the tree contamination is also larger. Data is currently not available to test (14), but we may instead consider

$$S_{h}^{\prime} \equiv \frac{2 \Gamma_{h}(\rho^{0} K^{*-})}{\Gamma_{h}(\rho^{-} K^{0})} = \left| 1 + p_{h}^{\text{EW}} \right|^{2} + \Delta_{h}^{\prime}.$$  \hspace{1cm} (15)

Following the same strategy as above, we obtain $\Delta_{h}^{\prime} = -0.1 \pm 0.0$, and $S_{h}^{\prime} = 0.5 \pm 0.1 [1.2 \pm 0.1]$. In the absence of direct CP asymmetries $S_{h}$ is directly related to the corresponding ratio of polarization fractions $f_{h}^{\prime} \equiv f_{h}(\rho^{0} K^{*-})/f_{h}(\rho^{-} K^{0})$. Including a theoretical estimate of the CP asymmetries, we obtain

$$f_{h}^{\prime} = 1.3 \pm 0.1 [1.1 \pm 0.1],$$  \hspace{1cm} (16)

$$f_{h}^{\prime} = 1 - f_{h}(\rho^{0} K^{*-})/1 - f_{h}(\rho^{-} K^{0}) = 0.4 \pm 0.1 [0.8 \pm 0.1].$$  \hspace{1cm} (17)

This can be compared to the experimental values $f_{h}^{\prime\text{exp}} = 1.45^{+0.64}_{-0.58}$, $f_{h}^{\prime\text{exp}} = 0.13^{+0.44}_{-0.11} [1]$.

Finally, we comment on the possibility of detecting the presence of new flavour-changing neutral currents in the form of an electromagnetic penguin operator with opposite chirality, $Q_{7}^{\pm}$. For this analysis, one must isolate experimentally the positive-helicity amplitudes. Theoretically, all positive-helicity amplitudes are suppressed, except for the electromagnetic penguin contribution $\Delta_{\gamma}^{\text{EW}}$ to the electroweak penguin amplitude. In the naive factorization approximation $X_{+} = r X_{-}$, where $r$ is a $\Lambda/m_{b}$-suppressed form factor ratio, while $\Delta_{\gamma}^{\text{EW}} \approx C_{7}^{+}/C_{7}^{-} \Delta r_{\gamma}^{\text{EW}}$ is suppressed only by the ratio of Wilson coefficients (see (11)). A conservative analysis of the $b \rightarrow s \gamma$ branching fraction constrains $C_{7}^{+}/C_{7}^{-} < 0.5$, hence it is possible that the suppression is weak. This would lead to $P_{\gamma}^{\text{EW}} \gg P_{\gamma}$, in which case the positive-helicity decay rates of the $\rho^{0} K^{*}$ final states are much larger than the $\rho^{0} K^{*}$ ones.

A complete angular analysis of the $\rho K^{*}$ system should allow a determination of $P_{\gamma}^{\text{EW}}$ even when it is not dominant, possibly allowing a limit on $C_{7}^{+}/C_{7}^{-}$ of order $r \approx 0.1$.

In conclusion, we discussed an electromagnetic penguin contribution to non-leptonic $B$ decays that has previously been overlooked. It is the largest contribution to the negative-helicity electroweak penguin amplitude, and substantially modifies the theoretical expectations for polarization observables in $b \rightarrow s$ penguin-dominated decays, in particular to the $\rho^{0} K^{*}$ final states. These observables may therefore be of considerable interest to the search for electromagnetic flavour-changing neutral currents with chirality equal or opposite to the SM.

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