Polarization in $B \to \phi K^*$ Decays and Probe of New Physics

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The observation of sizable transverse fractions for $B \to \phi K^*$ decays is inconsistent with the factorization expectation. The tensor-type and/or scalar-type new-physics operators can account for the discrepancy and the observed $f_\perp / f_\parallel \approx 1$. Analogously, the transverse fractions of $B \to h_1(1380)K^*$ decays can become sizable due to new-physics contributions. On the other hand, it was argued that the $B \to \phi K^*$ data can be accounted for in the standard model if including the annihilation topologies. If it is true, we further show that the same annihilation effects can greatly enhance *only* the longitudinal fraction of $B \to h_1(1380)K^*, b_1(1235)K^*$ but contribute negligibly to the transverse components. The measurements of these decays can thus help us to realize the role of annihilation topologies in B decays and offer a theoretically clean window to search for the evidence of new physics.

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1. Introduction

The BaBar and Belle collaborations have recently measured $B \to \phi K^*$ decays and showed that the total transverse fractions with $f_\perp$ (the perpendicular fraction) $\simeq f_\parallel$ (the parallel fraction) are about equal to the longitudinal one [1]. In the standard model (SM) the relation for different helicity amplitudes is $\overline{H}_{00} : \overline{H}_{--} : \overline{H}_{++} \sim \mathscr{O}(1) : \mathscr{O}(1/m_b) : \mathscr{O}(1/m_b^2)$ and thus the transverse fractions are suppressed by $1/m_b^2$. One may therefore resort to new physics (NP) to explain the observations. However, several NP proposals seem to be ruled out compared with the data (see discussion in [2]). It was first recognized in [2] that only two classes of NP operators are relevant in resolving the transverse anomaly in the ϕK^* modes. The first class of operators with structures $\sigma(1-\gamma_5) \otimes \sigma(1-\gamma_5)$ and $(1-\gamma_5) \otimes (1-\gamma_5)$ contributes to helicity amplitudes as $\overline{H}_{00} : \overline{H}_{--} : \overline{H}_{++} \sim \mathscr{O}(1/m_b) : \mathscr{O}(1/m_b^2) : \mathscr{O}(1)$, while the second class of operators with structures $\sigma(1+\gamma_5) \otimes \sigma(1+\gamma_5)$ and $(1+\gamma_5) \otimes (1+\gamma_5)$ results in $\overline{H}_{00} : \overline{H}_{++} : \overline{H}_{--} \sim \mathscr{O}(1/m_b) : \mathscr{O}(1/m_b^2) : \mathscr{O}(1)$.

2. New-physics effects

The relevant NP effective Hamiltonian $\mathscr{H}^{\rm NP}$ for $b \to s\bar{s}s$ processes [2], is

$$\mathscr{H}^{\rm NP} = \frac{G_F}{\sqrt{2}} \sum_{i=15-18,23-26} c_i(\mu) O_i(\mu) + H.c.\,, \tag{2.1}$$

where the scalar-type operators are

$$\begin{aligned} O_{15} &= \bar{s}(1+\gamma^5)b\,\bar{s}(1+\gamma^5)s\,, \quad O_{16} = \bar{s}_\alpha(1+\gamma^5)b_\beta\,\bar{s}_\beta(1+\gamma^5)s_\alpha\,, \\ O_{17} &= \bar{s}(1-\gamma^5)b\,\bar{s}(1-\gamma^5)s\,, \quad O_{18} = \bar{s}_\alpha(1-\gamma^5)b_\beta\,\bar{s}_\beta(1-\gamma^5)s_\alpha\,, \end{aligned} \tag{2.2}$$

and the tensor-type operators are

$$\begin{aligned} O_{23} &= \bar{s}\sigma^{\mu\nu}(1+\gamma^5)b\,\bar{s}\sigma_{\mu\nu}(1+\gamma^5)s\,, \quad O_{24} = \bar{s}_\alpha\sigma^{\mu\nu}(1+\gamma^5)b_\beta\,\bar{s}_\beta\sigma_{\mu\nu}(1+\gamma^5)s_\alpha\,, \\ O_{25} &= \bar{s}\sigma^{\mu\nu}(1-\gamma^5)b\,\bar{s}\sigma_{\mu\nu}(1-\gamma^5)s\,, \quad O_{26} = \bar{s}_\alpha\sigma^{\mu\nu}(1-\gamma^5)b_\beta\,\bar{s}_\beta\sigma_{\mu\nu}(1-\gamma^5)s_\alpha\,, \end{aligned} \tag{2.3}$$

with α, β being the color indices. By the Fierz transformation, $O_{15,16}$ and $O_{17,18}$ operators can be expressed in terms of linear combination of $O_{23,24}$ and $O_{25,26}$ operators, respectively, i.e.,

$$O_{15(17)} = \frac{1}{12}O_{23(25)} - \frac{1}{6}O_{24(26)}\,, \quad O_{16(18)} = \frac{1}{12}O_{24(26)} - \frac{1}{6}O_{23(25)}\,. \tag{2.4}$$

The helicity amplitudes for $\overline{B} \to \phi \overline{K}$ decays due to the NP operators read (in units of $G_F/\sqrt{2}$)

$$\begin{aligned} \overline{A}_0^{NP} &= -4i f_\phi^\perp m_B^2 [\tilde{a}_{23} - \tilde{a}_{25}] \left[h_2 T_2(m_\phi^2) - h_3 T_3(m_\phi^2)\right], \\ \overline{A}_\parallel^{NP} &= 4i\sqrt{2} f_\phi^\perp (m_B^2 - m_{K^*}^2)(\tilde{a}_{23} - \tilde{a}_{25}) T_2(m_\phi^2), \\ \overline{A}_\perp^{NP} &= 8i\sqrt{2} f_\phi^\perp m_B p_c (\tilde{a}_{23} + \tilde{a}_{25}) T_1(m_\phi^2), \end{aligned} \tag{2.5}$$

where

$$\tilde{a}_{23} = a_{23} + \frac{a_{24}}{2} - \frac{a_{16}}{8}\,, \quad \tilde{a}_{25} = a_{25} + \frac{a_{26}}{2} - \frac{a_{18}}{8}\,, \tag{2.6}$$

are defined as $\tilde{a}_{23} = -|\tilde{a}_{23}| e^{i\delta_{23}} e^{i\phi_{23}}, \tilde{a}_{25} = |\tilde{a}_{25}| e^{i\delta_{25}} e^{i\phi_{25}}$ with $\delta_{23,25}$ and $\phi_{23,25}$ being the strong phases and NP weak phases, respectively. Here we have defined

$$a_{2i(2i-1)} = c_{2i(2i-1)} + \frac{c_{2i-1(2i)}}{N_c} + \text{nonfactorizable corrections}\,, \quad \text{with i} \in \text{integer number}\,. \tag{2.7}$$

2.1 NP scenario I with $O_{15,16,23,24}$ absent

This scenario gives $\overline{H}_{++} \gg \overline{H}_{--}$ which is consistent with the standard model expectation, and the NP effects characterized by $O_{17,18,25,26}$ operators are lumped into the single effective coefficient $\tilde{a}_{25}$. In the best fit analysis, we have

$$|\tilde{a}_{25}| = (2.0 \pm 0.3) \times 10^{-4}, \quad \delta_{25} = 1.00 \pm 0.30, \quad \phi_{25} = -0.02 \pm 0.06. \tag{2.8}$$

2.2 Scenario II with $O_{17,18,25,26}$ absent

We get $\overline{H}_{--} \gg \overline{H}_{++}$ if $O_{15,16}, O_{23,24}$ operators are dominant. In this scenario, we obtain

$$|\tilde{a}_{23}| = (1.5 \pm 0.3) \times 10^{-4}, \quad \delta_{23} = -0.47 \pm 0.20, \quad \phi_{23} = -0.07 \pm 0.06. \tag{2.9}$$

It is interesting to note that the phase difference for $\overline{A}_\perp$ and $\overline{A}_\parallel$ reads

$$\arg(\overline{A}_\perp) - \arg(\overline{A}_\parallel) \approx \pi \tag{2.10}$$

in the scenario I, but becomes

$$\arg(\overline{A}_\perp) - \arg(\overline{A}_\parallel) \approx 0 \tag{2.11}$$

in the scenario II. These two possible NP solutions can be further distinguished in $B \to h_1(1380) K^*$ measurements for which there is no phase ambiguity existing between the two NP scenarios [3].

3. Probe of new physics

The possible NP effects can be further tested from measurements of the factorization-suppressed $\overline{B} \to h_1(1380)\overline{K}$ decays, where $h_1(1380)$ is a 1^1P_1 state in the quark-model description. The $\overline{B} \to h_1(1380)\overline{K}$ amplitudes vanish in the factorization limit. Nevertheless, the light-cone distribution amplitudes of $h_1(1380)$ defined by the bi-local vector and axial-vector currents are greatly antisymmetric under the exchange of *quark* and *anti-quark* momentum fractions, so that “only" the longitudinal fraction receives sizable QCD corrections. On the other hand, interestingly, the local tensor operator can couple to the transversely polarized $h_1(1380)$ meson. Thus, in complete analogy to the $B \to \phi K^*$ decays, the NP tensor operators could enhance the transverse fractions of the $h_1(1380)\overline{K}$ modes. The $\overline{B} \to h_1(1380)\overline{K}$ decay amplitudes in the transversity basis, in units of $G_F/\sqrt{2}$, due to the NP operators read

$$\begin{aligned}
\overline{A}_0^{NP} &= 4 f_{h_1}^\perp m_B^2 (\tilde{a}_{23} + \tilde{a}_{25}) \left[h_2 T_2(m_{h_1}^2) - h_3 T_3(m_{h_1}^2) \right] , \\
\overline{A}_\parallel^{NP} &= -4\sqrt{2} f_{h_1}^\perp (m_B^2 - m_{K^*}^2)(\tilde{a}_{23} + \tilde{a}_{25}) T_2(m_{h_1}^2), \\
\overline{A}_\perp^{NP} &= -8\sqrt{2} f_{h_1}^\perp m_B p_c (\tilde{a}_{23} - \tilde{a}_{25}) T_1(m_{h_1}^2) .
\end{aligned} \tag{3.1}$$

The results are shown in Table 1 [3]. Unlike the $\phi\overline{K}^*$ modes, the two possible NP solutions are distinguishable in the $h_1(1380)K^*$ modes since $\arg(A_\parallel/A_0)$ (scenario 1) $\neq -\arg(A_\parallel/A_0)$(scenario 2).

New physics	Modes	$\mathrm{BR_{tot}}$	$\mathrm{BR}_\parallel$	$\mathrm{BR}_\perp$	$\arg(\frac{A_\parallel}{A_0})$	$\arg(\frac{A_\perp}{A_0})$
Scenario 1:	$h_1 K^{*0}$	14.5 ± 4.0	3.2 ± 1.5	2.0 ± 1.0	-2.23 ± 0.25	0.49 ± 0.15
Scenario 2:	$h_1 K^{*0}$	8.5 ± 2.0	2.0 ± 0.5	1.8 ± 0.5	-0.86 ± 0.20	-0.97 ± 0.20

Table 1: New-physics predictions for $\overline{B} \to h_1(1380)\overline{K}^*$ modes, where the branching ratios (BRs) are given in units of 10^{-6} and phases in radians. $\tilde{a}_{25}$ and $\tilde{a}_{23}$ are used with constraints by the $B \to \phi K^*$ data.

4. Probe of annihilation topologies in the standard model

Within the standard model framework, it had been argued [4] that the annihilation amplitudes, suppressed by $1/m_b^2$ but logarithmically enhanced, could account for the $B \to \phi K^*$ data if a moderate value of the BBNS parameter ρ_A [5] is applied. We found that if the large transverse fractions of ϕK^* modes mainly originate from the annihilation topologies, then the resultant enhancement should be observed only in the longitudinal component of $h_1 K^*$ and $b_1 K^*$ modes such that the resulting $f_L(h_1(1380)K^*)$ and $f_L(b_1^+(1235)K^{*-})$ could be even larger than $f_L(\phi K^*)$ and $f_L(\rho^+ K^{*-})$, respectively. Note that h_1 and b_1 are 1^1P_1 states. The annihilation amplitudes for $\overline{B} \to h_1 \overline{K}^*$ read

$$A_3^{f,0}(h_1\overline{K}^*) \approx -18\pi\alpha_s(X_A^0 - 2)\left[\frac{2m_{h_1} f_{h_1}^\perp}{m_b f_{h_1}}(2X_A^0 - 1) - \frac{2m_{K^*} a_1^{h_1,\parallel} f_{K^*}^\perp}{m_b f_{K^*}}(6X_A^0 - 11)\right], \qquad (4.1)$$

$$A_3^{f,-}(h_1\overline{K}^*) \approx -18\pi\alpha_s(X_A^- - 1)\left[\frac{2m_{K^*} f_{h_1}^\perp}{m_b f_{h_1}}(2X_A^- - 3) - \frac{2m_{h_1} a_1^{h_1,\parallel} f_{K^*}^\perp}{m_b f_{K^*}}\left(2X_A^- - \frac{17}{3}\right)\right], \qquad (4.2)$$

and $A_3^{f,+}(h_1\overline{K}^*) \approx 0$, where $X_A^h = (1+\rho_A^h e^{i\varphi_A^h})\ln(m_B/\Lambda_h)$ with $\rho_A^h < 1$. The numerical results of some interesting modes are listed in Table 2. According to the annihilation scenario, we obtained $f_T(\rho^+K^{*-}) \simeq 0.23 \sim 0.46$, $2\mathrm{BR_T}(\rho^0 K^{*-}) \sim \mathrm{BR_T}(\rho^-\overline{K}^{*0}) \sim \mathrm{BR_T}(\rho^+K^{*-})$. We also find some $B \to 1^3P_1 V$ processes can offer further tests of the present NP scenarios and annihilation topologies [6].

	$\mathrm{BR^{wo}_{tot}}$	$\mathrm{BR^{wo}_\parallel}$	$\mathrm{BR^{wo}_\perp}$	$\mathrm{BR^{w}_{tot}}$	$\mathrm{BR^{w}_\parallel}$	$\mathrm{BR^{w}_\perp}$
$\overline{B}^0 \to h_1(1380)K^{*0}$	$3.2^{+1.5}_{-1.2}$	$\lesssim 0.2$	$\lesssim 0.2$	$12.0^{+4.1}_{-3.0}$	$\lesssim 1.0$	$\lesssim 1.0$
$\overline{B}^0 \to b_1^+(1235)K^{*-}$	1.7 ± 1.3	$\lesssim 0.01$	$\lesssim 0.01$	7.0 ± 3.5	$\lesssim 0.3$	$\lesssim 0.3$
$\overline{B}^0 \to \rho^+K^{*-}$	6.3 ± 2.0	0.2 ± 0.1	0.2 ± 0.1	6.2 ± 2.0	1.2 ± 0.7	1.2 ± 0.7

Table 2: CP-averaged branching ratios (in units of 10^{-6}) without/with annihilation contributions denoted as $\mathrm{BR^{wo}}/\mathrm{BR^{w}}$.

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