Searching for new physics in the angular distribution of $B_d^0 \to \phi K^{*0}$ decay

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Abstract

Motivated by the possible discrepancy between the observed CP asymmetry and that of the standard model expectation in the decay mode $B^0 \to \phi K_S$, we study the corresponding vector vector decay mode $B^0 \to \phi K^{*0}$. In order to obtain decisive information regarding the CP violation effect, we made the angular distribution analysis of the decay products, where both the outgoing vector mesons decay into two pseudoscalars. Furthermore, we study the possible effects of new physics using the angular distribution observables.
1 Introduction

The study of $B$ physics provides a great opportunity and an ideal testing ground to obtain a deep insight into the flavor structure of the standard model (SM) and the origin of CP violation. In view of the wide variety of decay channels one can look for many different observables, providing stringent tests for the consistency of the model. The goal of the $B$ factories is not only to test the SM picture but also to discover the evidence of new physics (NP). Recently, the measurement of the time dependent CP asymmetries in the $B \rightarrow \psi K_S$ decays has led to the confirmation of CP violation in $B$ systems. The observed world average of the asymmetry, i.e., $\sin 2\beta$ is given by

$$\sin(2\beta)_{\psi K_S} = 0.734 \pm 0.054,$$

which is consistent with the SM expectation. However, this result does not exclude interesting CP violating new physics effects in other $B$ decays. Since the decay $B \rightarrow \psi K_S$ is dominated by the tree level $b \rightarrow c\bar{c}s$ transition in the SM, the NP contributions to its amplitude are naturally suppressed. However, at the loop level NP may give large contributions to the $B^0 - \bar{B}^0$ mixing as well as to the loop induced decay amplitudes. The former effects are universal to all decay modes while the new physics effects to the decay amplitudes are nonuniversal and process dependent. Thus the comparison of time dependent rate asymmetries in different decay channels, measuring the same weak phase in the SM, could provide evidence on new physics in the $B$ meson decay amplitudes.

$B$ decays involving the $b \rightarrow sss$ transition such as $B \rightarrow \phi K, B \rightarrow \eta' K, \phi K^*, \cdots$, proceed through the loop induced penguin diagrams. These processes provide information on the Cabibbo-Kobayashi-Maskawa (CKM) matrix element $V_{ts}$ and are sensitive to physics beyond the SM. They can also be used for independent measurement of the CP violating parameter $\sin(2\beta)$, and the uncertainty within the SM, for the decay mode $B \rightarrow \phi K_S$ is estimated to be

$$|\sin(2\beta)_{\psi K_S} - \sin(2\beta)_{\phi K_S}| \lesssim \mathcal{O}(\lambda^2).$$

(2)

Recently Belle [3] and BABAR [4] have measured $\sin(2\beta)_{\phi K_S}$ with an average

$$\sin(2\beta)_{\phi K_S} = -0.39 \pm 0.41,$$

(3)

which has a 2.7$\sigma$ deviation from the observed value of $\sin(2\beta)_{\psi K_S}$. The most recent updated average value of the asymmetry [5] is

$$\sin(2\beta)_{\phi K_S} = -0.15 \pm 0.33.$$

(4)

Thus the discrepancy between the measured values of $\sin(2\beta)_{\psi K_S}$ and $\sin(2\beta)_{\phi K_S}$ may be a possible indication of new physics effects in the decay amplitude of $B$ system.

Recently, several new physics phenomena have been studied to explain the above discrepancy [6, 7, 8, 9]. If new physics effects indeed are present in the decay mode $B \rightarrow \phi K_S$, then one can expect to observe similar effects in other modes having the same internal quark structure (in fact it is this speculation which motivated us to undertake the study of this...
Therefore, it is also important to explore other signals of new physics in order to corroborate this result. One way to search for new physics effects is to look for direct CP violation in decay modes which are having a single decay amplitude in the SM. It should be reminded here that in order to observe direct CP violation there should be two interfering decay amplitudes with different strong and weak phases. An observation of direct CP violation in such modes, is an unambiguous signal of new physics. However, non-vanishing of the direct CP violation requires the relative strong phases between the SM and NP amplitudes to be nonzero. Therefore, if the relative strong phase between the two interfering amplitudes is zero, one cannot get the new physics information, even if it would be present there. However, still we have an opportunity which in turn can help us to find out the evidence of NP. In fact, if one considers \(B\) decays to two vector mesons [10] then one can show that many signals of new physics effect emerge including those which are nonzero even if the strong phase difference vanish. Therefore, the studies of \(B\) meson decaying to two vector modes are likely to be the major contenders to look for NP.

In this paper we intend to study the new physics effects in the decay mode \(\bar{B}^0 \to \phi K^{*0}\). Recently, the Belle [11] and BABAR [12] collaborations have reported the full angular analysis of \(B \to \phi K^{*}\) decays. The Belle measurements are as

\[
\text{Br}(B^0 \to \phi K^{*0}) = (10.0^{+1.6+0.7}_{-1.5-0.8}) \times 10^{-6},
\]

\[
|\hat{A}_0|^2 = 0.43 \pm 0.09 \pm 0.04, \quad |\hat{A}_\perp|^2 = 0.41 \pm 0.10 \pm 0.04,
\]

and

\[
|\hat{A}_\parallel|^2 = 1 - |\hat{A}_0|^2 - |\hat{A}_\perp|^2,
\]

\[
\arg(\hat{A}_\parallel) = -2.57 \pm 0.39 \pm 0.09, \quad \arg(\hat{A}_\perp) = 0.48 \pm 0.32 \pm 0.06, \tag{5}
\]

and the BABAR data are

\[
\text{Br}(B^0 \to \phi K^{*0}) = (11.2 \pm 1.3 \pm 0.8) \times 10^{-6},
\]

\[
\frac{\Gamma_L}{\Gamma} = 0.65 \pm 0.07 \pm 0.02, \quad A_{CP} = 0.04 \pm 0.12 \pm 0.02. \tag{6}
\]

The average branching ratio of Belle and BABAR measurements is given as

\[
\text{Br}(B^0 \to \phi K^{*0}) = (10.7 \pm 1.1) \times 10^{-6}. \tag{7}
\]

From the theoretical point of view, recently, this decay mode has been studied within the SM in the framework of QCD factorization [13] and PQCD approach [14]. Although the branching ratio in PQCD approach is found to be consistent with the experiment, but other observables like the helicity amplitudes do not agree with the current experimental data. At present, it appears that new physics effects indeed are present in the \(B \to \phi K_S\) mode. Driven by the experimental activity and the possible discrepancy in the CP asymmetry in the \(\phi K_S\) sector, it is therefore interesting to see the effects of NP in the decay mode \(B \to \phi K^{*0}\), which is our prime objective in this paper. Here we consider two scenarios beyond the SM, the R-parity violating (RPV) supersymmetric model and the model with an extra vector-like down quark (VLDQ). It has been shown very recently that these two models can explain the observed 2.7\(\sigma\) discrepancy in \(B \to \phi K_S\) mode [7, 8, 9].
The paper is organised as follows. Section II includes a general description of the angular distributions and the observables in \( B \to VV \) decays, while in Section III we analyze the particular case of \( B^0 \to \phi K^{*0} \) in the SM. The new physics effects from VLDQ model and RPV model are considered in sections III and IV respectively and in Section V we present some concluding remarks.

2 Observables and angular distributions in \( B \to VV \)

Let us consider the decay of a \( B \) meson into two vector mesons (\( \phi \) and \( K^* \)), followed by the decay \( \phi \to K^+ K^- \) and \( K^{*0} \to K^+ \pi^- \) respectively. Following the notations of Ref. [15], the normalized differential angular distribution can be written as

\[
\frac{1}{\Gamma} \frac{d^3 \Gamma}{d \cos \theta_1 d \cos \theta_2 d \psi} = \frac{9}{8 \pi} \left\{ L_1 \cos^2 \theta_1 \cos^2 \theta_2 + \frac{L_2}{2} \sin^2 \theta_1 \sin^2 \theta_2 \cos^2 \psi \\
+ \frac{L_3}{2} \sin^2 \theta_1 \sin^2 \theta_2 \sin^2 \psi + \frac{L_4}{2 \sqrt{2}} \sin 2 \theta_1 \sin 2 \theta_2 \cos \psi \\
- \frac{L_5}{2 \sqrt{2}} \sin 2 \theta_1 \sin 2 \theta_2 \sin \psi - \frac{L_6}{2} \sin^2 \theta_1 \sin^2 \theta_2 \sin 2 \psi \right\},
\]

where \( \theta_1 (\theta_2) \) is the angle between the three-momentum of \( K^+ (K^+) \) in the \( \phi \) (\( K^{*0} \)) rest frame and the three-momentum of \( \phi (K^{*0}) \) in the \( B \) rest frame, and in Eq. (8) \( \psi \) is the angle between the normals to the planes defined by \( K^+ K^- \) and \( K^+ \pi^- \), in the \( B \) rest frame. The coefficients \( L_i \) can be expressed in terms of three independent amplitudes, \( A_0, A_\parallel \) and \( A_\perp \), which correspond to the different polarization states of the vector mesons \( \phi \) and \( K^{*0} \) as

\[
L_1 = |A_0|^2, \quad L_4 = \text{Re}[A_\parallel A_0^*], \\
L_2 = |A_\parallel|^2, \quad L_5 = \text{Im}[A_\perp A_0^*], \\
L_3 = |A_\perp|^2, \quad L_6 = \text{Im}[A_\perp A_\parallel^*].
\]

In the above \( A_0, A_\parallel \), and \( A_\perp \) are complex amplitudes of the three helicity states in the transversity basis. The CP odd and CP even fractions of the decay \( B \to \phi K^{*0} \) are given by \( |A_\perp|^2 \) and \( (|A_0|^2 + |A_\parallel|^2) \) respectively.

It should be noted here that only six of the nine possible observables given by the squared amplitude \( A^* A \) can be measured independently. This is because of the fact that both the daughter vector mesons (\( \phi \) and \( K^* \)) are considered to decay into two spin zero particles.

The decay mode \( B \to V_1 V_2 \) can also be described in the helicity basis, where the amplitude for the helicity matrix element can be parametrized as [16]

\[
H_{\lambda} = \langle V_1(\lambda)V_2(\lambda)|H_{eff}|B^0 \rangle
\]
\[ \varepsilon_{1\mu}^*(\lambda) \varepsilon_{2\nu}^*(\lambda) \left[ ag^{\mu\nu} + \frac{b}{m_1 m_2} p^\mu p^\nu + \frac{ic}{m_1 m_2} e^{\nu\alpha\beta} p_1 \alpha p_3 \right], \quad (10) \]

where \( p \) is the \( B \) meson momentum and \( \lambda = 0, \pm 1 \) are the helicity of both the vector mesons. In the above expression \( m_i, p_i \) and \( \varepsilon_i \) \( (i = 1, 2) \) stand for their masses, momenta and polarization vectors respectively. Furthermore, the three invariant amplitudes \( a, b, \) and \( c \) are related to the helicity amplitudes by

\[ H_{\pm 1} = a \pm c \sqrt{x^2 - 1}, \quad H_0 = -ax - b(x^2 - 1), \quad (11) \]

where \( x = (p_1 \cdot p_2)/m_1 m_2 = (m_B^2 - m_1^2 - m_2^2)/(2m_1 m_2) \).

The corresponding decay rate using the helicity basis amplitudes can be given as

\[ \Gamma = \frac{p_{cm}}{8\pi m_B^2} \left( |H_0|^2 + |H_{+1}|^2 + |H_{-1}|^2 \right), \quad (12) \]

where \( p_{cm} \) is the magnitude c.o.m. momentum of the outgoing vector particles. It is also convenient to express the relative decay rates into \( V \) meson states with longitudinal and transverse polarizations as

\[ \frac{\Gamma_L}{\Gamma_0} = \frac{|H_0|^2}{|H_0|^2 + |H_{+1}|^2 + |H_{-1}|^2}, \]
\[ \frac{\Gamma_T}{\Gamma_0} = \frac{|H_{+1}|^2 + |H_{-1}|^2}{|H_0|^2 + |H_{+1}|^2 + |H_{-1}|^2}. \quad (13) \]

The amplitudes in transversity and helicity basis are related to each other through the following relations

\[ A_\perp = \frac{H_{+1} - H_{-1}}{\sqrt{2}}, \quad A_\parallel = \frac{H_{+1} + H_{-1}}{\sqrt{2}}, \quad A_0 = H_0. \quad (14) \]

Correspondingly, the coefficients \( L_i \) can also be written in terms of the parameters \( a, b, \) and \( c \) as

\[ L_1 = |xa + (x^2 - 1)b|^2, \quad L_4 = -\sqrt{2} \left[ x |a|^2 + (x^2 - 1) \text{Re}(ab^*) \right], \]
\[ L_2 = 2 |a|^2, \quad L_5 = -\sqrt{2} (x^2 - 1) \left[ x \text{Im}(a^*c) + (x^2 - 1) \text{Im}(b^*c) \right], \]
\[ L_3 = 2 (x^2 - 1) |c|^2, \quad L_6 = 2 \sqrt{x^2 - 1} \text{Im}(a^*c). \quad (15) \]

Similar to the \( H_\lambda \) amplitudes, one can also write the corresponding amplitudes for the complex conjugate process. The helicity amplitudes \( \bar{H}_\lambda \) for the decay \( \bar{B} \rightarrow \bar{V}_1 \bar{V}_2 \), where \( \bar{V}_1 \) and \( \bar{V}_2 \) are the antiparticles of \( V_1 \) and \( V_2 \) respectively, have the same decomposition with

\[ a \rightarrow \bar{a}, \quad b \rightarrow \bar{b} \quad \text{and} \quad c \rightarrow -\bar{c}. \quad (16) \]
here in general, the parameters \(a, b,\) and \(c\) are complex numbers. One can then write these amplitudes as

\[
    a = |a| e^{i(\delta_a + \varphi_a)},
\]

where \(\delta\) and \(\varphi\) stand for “strong” (CP-conserving) and “weak” (CP-violating) phases respectively. In fact, the parameter \(a\) can have contributions from different interfering decay amplitudes. Since the decay \(B \to \phi K^*\) receives dominant contribution only from the one loop \(b \to s\bar{s} s\) penguin diagram with top quark in the loop (i.e, it is described by a single weak decay amplitude), we consider only one term in the amplitude \(a\). The \(\bar{a}\) then can be obtained from \(a\), by changing the sign of weak phase. Similar relations as that of (17) can be written for parameters \(b\) and \(c\).

In our analysis, we will take into account both the decay \(B^0 \to \phi K^*\) and its CP-conjugate process, \(\bar{B}^0 \to \phi \bar{K}^*\). In fact, there are several ways for CP violation to manifest itself. But, the most familiar one is in the partial rate asymmetries. Since there are three differential decay amplitudes, the partial rate asymmetries may show up in either of them. These asymmetries can be studied by measuring the coefficients of first three terms in Eq.(8) for \(B^0\) and \(\bar{B}^0\) decays and comparing those coefficients. In addition to these, CP violation can also be observed in the interfering amplitudes, i.e., in the measurement of the coefficients of last three terms of Eq. (8). Notice, however, that without separating the observables of \(B^0\) and \(\bar{B}^0\) decays, the relevant information on CP violation cannot be extracted. Therefore, one must obtain the angular distribution for \(B^0 \to \phi K^*\) and \(\bar{B}^0 \to \phi \bar{K}^*\) decays separately and determine the coefficients \(L_{1-6}\) in each case.

Now, in principle, from the angular analysis of \(B^0 \to \phi K^*\) decays one can measure twelve observables, these are in fact the coefficients \(L_i\) and \(\bar{L}_i\) with \(i = 1\) to \(6\). The CP violating effects in these observables are given as

\[
    C_1 = L_1 - \bar{L}_1 = -4x(x^2 - 1)|a| |b| \sin \delta_{ab} \sin \varphi_{ab},
\]

\[
    C_2 = L_2 - \bar{L}_2 = 0,
\]

\[
    C_3 = L_3 - \bar{L}_3 = 0,
\]

\[
    C_4 = L_4 - \bar{L}_4 = 2\sqrt{2}(x^2 - 1)|a| |b| \sin \delta_{ab} \sin \varphi_{ab},
\]

\[
    C_5 = L_5 + \bar{L}_5 = -2\sqrt{2}(x^2 - 1)|c| \left[ x|a| \cos \delta_{ca} \sin \varphi_{ca} + (x^2 - 1)|b| \cos \delta_{cb} \sin \varphi_{cb} \right],
\]

\[
    C_6 = L_6 + \bar{L}_6 = 4\sqrt{(x^2 - 1)|a| |c| \cos \delta_{ca} \sin \varphi_{ca}},
\]

where \(\delta_{ij} = \delta_i - \delta_j\) and \(\varphi_{ij} = \varphi_i - \varphi_j\). It is important to note that the CP violating observables \(C_5\) and \(C_6\) do not require FSI strong phase differences and especially sensitive to CP violating weak phases.

So far, we have limited our discussion to that of within the framework of the SM and presented various combinations in which CP violation effects will show up. We are now ready to explore the effects of new physics.

Now in the presence of new physics the total invariant amplitude may be written as

\[
    a_T = a_{SM} + a_{NP} = a_{SM}[1 + r_a e^{i(\delta_a + \varphi_a)}],
\]

6
where \( r_a = |a_{NP}/a_{SM}| \), \((a_{SM} \text{ and } a_{NP} \text{ correspond to the SM and NP amplitudes})\) and \( \delta^n_a (\varphi^n_a) \) is the relative strong (weak) phase between the SM and NP amplitudes. Similar expressions can be written for the other two amplitudes \( b \) and \( c \).

Incorporating the generic new physics contribution we write the modified observables and after some algebra we arrive at the new \( C \)'s as given below. Thus, in the presence of new physics the CP violating observables \( C_{(1-6)} \) read as

\[
C_1 = -4 \left[ x(x^2 - 1) |a| |b| \sin\delta_{ab} \varphi_{ab} + x^2 |a|^2 r_a \sin\delta^n_a \sin\varphi^n_a + (x^2 - 1)^2 |b|^2 r_b \sin\delta^n_b \sin\varphi^n_b \right. \\
+ x(x^2 - 1) |a| |b| \left( r_a \sin(\delta_{ab} + \delta^n_a) \sin(\varphi_{ab} + \varphi^n_a) + r_b \sin(\delta_{ab} + \delta^n_b) \sin(\varphi_{ab} + \varphi^n_b) \right) \\
\left. + r_a r_b \sin(\delta_{ab} + \delta^n_{ab}) \sin(\varphi_{ab} + \varphi^n_{ab}) \right],
\]

\[
C_2 = -8 |a|^2 r_a \sin\delta^n_a \sin\varphi^n_a,
\]

\[
C_3 = -8 (x^2 - 1) |c|^2 r_c \sin\delta^n_c \sin\varphi^n_c,
\]

\[
C_4 = 2\sqrt{2} \left[ (x^2 - 1) |a| |b| \left( \sin\delta_{ab} \sin\varphi_{ab} + r_a \sin(\delta_{ab} + \delta^n_a) \sin(\varphi_{ab} + \varphi^n_a) \right) \\
+ r_b \sin(\delta_{ab} + \delta^n_b) \sin(\varphi_{ab} + \varphi^n_b) + r_a r_b \sin(\delta_{ab} + \delta^n_{ab}) \sin(\varphi_{ab} + \varphi^n_{ab}) \right) \\
+ 2 |a|^2 x r_a \sin\delta^n_a \sin\varphi^n_a],
\]

\[
C_5 = -2\sqrt{2} (x^2 - 1) |c| \left[ x |a| \left( \cos\delta_{ca} \sin\varphi_{ca} + r_c \cos(\delta_{ca} + \delta^n_c) \sin(\varphi_{ca} + \varphi^n_c) \right) \\
+ r_a \cos(\delta_{ca} - \delta^n_a) \sin(\varphi_{ca} - \varphi^n_a) + r_a r_c \cos(\delta_{ca} + \delta^n_{ca}) \sin(\varphi_{ca} + \varphi^n_{ca}) \right) \\
+ (x^2 - 1) |b| \left( \cos\delta_{cb} \sin\varphi_{cb} + r_c \cos(\delta_{cb} + \delta^n_c) \sin(\varphi_{cb} + \varphi^n_c) \right) \\
+ r_b \cos(\delta_{cb} - \delta^n_b) \sin(\varphi_{cb} - \varphi^n_b) + r_b r_c \cos(\delta_{cb} + \delta^n_{cb}) \sin(\varphi_{cb} + \varphi^n_{cb}) \right],
\]

\[
C_6 = 4\sqrt{(x^2 - 1) |a| |c|} \left[ \cos\delta_{ca} \sin\varphi_{ca} + r_c \cos(\delta_{ca} + \delta^n_c) \sin(\varphi_{ca} + \varphi^n_c) \\
+ r_a \cos(\delta_{ca} - \delta^n_a) \sin(\varphi_{ca} - \varphi^n_a) + r_a r_c \cos(\delta_{ca} + \delta^n_{ca}) \sin(\varphi_{ca} + \varphi^n_{ca}) \right],
\]

where \( \delta^n_{ij} = \delta^i_j - \delta^i_j \) and \( \varphi^n_{ij} = \varphi^i_j - \varphi^i_j \). After obtaining the expressions for the CP violating observables, in the presence of new physics, we now proceed to explore the specific cases. Before going to do that let us now first look at the relevant quantities in the SM. The discrepancy, if any, in the SM will necessitate the inclusion of NP to explain the same.

### 3 SM contribution to the amplitude \( B^0 \rightarrow \phi K^{*0} \)

Let us now focus on the decay \( B^0 \rightarrow \phi K^{*0} \). In the SM, this decay process proceeds through the quark level transition \( b \rightarrow s \bar{s}s \), which is induced by the QCD, electroweak (EW) and magnetic penguins. QCD penguins with the top quark in the loop contribute predominantly
to such process. However, since we are looking for NP, here we would like to retain all the contributions. The effective Hamiltonian describing the decay $b \to s\bar{s}s$ [17] is given as
\begin{equation}
H_{\text{eff}} = -\frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left( \sum_{j=3}^{10} C_j O_j + C_g O_g \right),
\end{equation}
where $O_3, \ldots, O_6$ and $O_7, \ldots, O_{10}$ are the standard QCD and EW penguin operators, respectively, and $O_g$ is the gluonic magnetic operator. Within the SM and at scale $M_W$, the Wilson coefficients $C_1(M_W), \ldots, C_{10}(M_W)$ at next to leading logarithmic order (NLO) and $C_g(M_W)$ at leading logarithmic order (LO) have been given in Ref. [18]. The corresponding QCD corrected values at the energy scale $\mu = m_b$ can be obtained using the renormalization group equation, as described in Ref. [19].

To calculate the $B$ meson decay rate, we use the factorization approximation to evaluate the hadronic matrix element $\langle O_i \rangle \equiv \langle \bar{K}^{*0} | O_i | \bar{B}^{0} \rangle$.

For evaluating the matrix element of the most relevant operator, i.e., $O_g$, we use the procedure of [20], where it has been shown that the operator $O_g$ is related to the matrix element of the QCD and electroweak penguin operators as
\begin{equation}
\langle O_g \rangle = -\frac{\alpha_s}{4\pi} \frac{m_b}{\sqrt{\langle q^2 \rangle}} \left[ \langle O_4 \rangle + \langle O_6 \rangle - \frac{1}{N_C} (\langle O_3 \rangle + \langle O_5 \rangle) \right].
\end{equation}
In the above equation $q^\mu$ is the momentum transferred by the gluon to the $(\bar{s}, s)$ pair. The parameter $\langle q^2 \rangle$ introduces certain uncertainty into the calculation. In the literature its value is taken in the range $1/4 \lesssim \langle q^2 \rangle/m_b^2 \lesssim 1/2$ [21], and we will use $\langle q^2 \rangle/m_b^2 = 1/2$ [19] in our numerical calculations.

Thus, in the factorization approach, the amplitude $A \equiv \langle \phi \bar{K}^{*0} | H_{\text{eff}} | \bar{B}^{0} \rangle$ of the decay $\bar{B}^{0} \to \phi \bar{K}^{*0}$ takes a form
\begin{equation}
A(\bar{B}^{0} \to \phi \bar{K}^{*0}) = -\frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[ a_3 + a_4 + a_5 - \frac{1}{2} (a_7 + a_9 + a_{10}) \right] X,
\end{equation}
where
\begin{equation}
X \equiv \langle \phi(\varepsilon_2, p_2) | \bar{s} \gamma_\mu (1 - \gamma_5) s | 0 \rangle \langle \bar{K}^{*0}(\varepsilon_1, p_1) | \bar{s} \gamma_\mu (1 - \gamma_5) b | \bar{B}^{0}(p) \rangle
\end{equation}
stands for the factorizable hadronic matrix element. The coefficients $a_i$ are given by
\begin{equation}
a_{2i-1} = C_{2i-1}^{\text{eff}} + \frac{1}{N_c} C_{2i-1}^{\text{eff}} C_{2i}^{\text{eff}}, \quad a_{2i} = C_{2i}^{\text{eff}} + \frac{1}{N_c} C_{2i-1}^{\text{eff}} C_{2i}^{\text{eff}},
\end{equation}
where $N_C$ is the number of colors.

In the factorization approximation the factorized matrix element $X$ (Eq. (24)) can be written, in general, in terms of form factors and decay constants. These are defined as [22]
\begin{equation}
\langle \phi(\varepsilon_2, p_2) | V_\mu | 0 \rangle = f_\phi m_\phi \varepsilon_{2\mu}^*,
\end{equation}
\[ \langle K^{*0}(\varepsilon_1, p_1)|V_\mu|\bar{B}(p)\rangle = -\frac{2}{m_{K^*} + m_B} \epsilon_{\mu \nu \alpha \beta} \varepsilon_1^{\nu} p^\alpha p_1^\beta V(q^2), \]

\[ \langle K^{*0}(\varepsilon_1, p_1)|A_\mu|B(p)\rangle = i \frac{2m_{K^*}(\varepsilon_1^\mu q)}{q^2} q_\mu A_0(q^2) + i (m_{K^*} + m_B) \left[ \varepsilon_1^\mu - \frac{(\varepsilon_1^\mu q)}{q^2} q_\mu \right] A_1(q^2) \]

\[ -i \left[ (p + p_1)_\mu - \frac{(m_B^2 - m_{K^*}^2)}{q^2} q_\mu \right] \frac{(\varepsilon_1^\mu q)}{m_{K^*} + m_B} A_2(q^2), \quad (26) \]

where \( V_\mu \) and \( A_\mu \) are the corresponding vector and axial-vector quark currents and \( q = p - p_1 \) is the momentum transfer. The vector and axial-vector form factors can be estimated from the analysis of semileptonic \( B \) decays, using the ansatz of pole dominance to account for the momentum dependences in the region of interest.

In this way the invariant amplitudes \( a, b, \) and \( c \) read as

\[ a = i P_{eff} f_\phi m_\phi (m_B + m_{K^*}) A_1^{B \rightarrow K^*}(m_\phi^2), \]

\[ b = -i P_{eff} f_\phi m_\phi \left( \frac{2m_{K^*}m_\phi}{m_B + m_{K^*}} \right) A_2^{B \rightarrow K^*}(m_\phi^2), \]

\[ c = -i P_{eff} f_\phi m_\phi \left( \frac{2m_{K^*}m_\phi}{m_B + m_{K^*}} \right) V^{B \rightarrow K^*}(m_\phi^2), \quad (27) \]

where

\[ P_{eff} = \frac{G_F}{\sqrt{2}} V_{ts}^* V_{tb} \left[ a_3 + a_4 + a_5 - \frac{1}{2}(a_7 + a_9 + a_{10}) \right]. \quad (28) \]

The values of the QCD improved effective coefficients \( a_i \) can be found in Ref. [19]. Now substituting the values of \( a_i \) for \( N_C=3 \), from Ref. [19], the value of the form factor \( V^{B \rightarrow K^*}(m_\phi^2) = 0.38 \), \( A_1^{B \rightarrow K^*}(m_\phi^2) = A_2^{B \rightarrow K^*}(m_\phi^2) = 0.34 \), and using the \( \phi \) meson decay constant \( f_\phi = 0.233 \text{ GeV} \) and \( \tau_B^{\phi} = 1.542 \times 10^{-12} \text{ sec} \) [23], we obtain the branching ratio in the SM as

\[ \text{BR}^{SM}(\bar{B} \rightarrow \phi K^{*0}) = 8.32 \times 10^{-6}, \quad (29) \]

which is slightly below the experimental limit (Eq. (7)).

However, the normalized polarization amplitudes (i.e., \(|\hat{A}_i|^2| = \frac{|A_i|^2}{(|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2)}\) with \( i = 0, ||, \perp \)) obtained are

\[ |\hat{A}_0|^2 = 0.869, \quad |\hat{A}_\parallel|^2 = 0.048, \quad |\hat{A}_\perp|^2 = 0.083, \quad (30) \]

which do not agree with the present experimental data (Eq. (5)). Furthermore, within the SM all the three invariant amplitudes \( a, b, \) and \( c \) have the vanishing weak phase (i.e., phase of \( V_{tb}V_{ts}^* \)). In the framework of the factorization approximation strong phases are originated by the final state interactions [24]. Moreover, these phases are the same for the amplitudes \( a, b, \) and \( c, \) since the combination of \( a_i \) coefficients in all cases is the same, as is encoded in \( P_{eff} \). Also we have the same \( P_{eff} \) appearing in all the amplitudes. In this way, within the factorization approximation we have

\[ \delta_a = \delta_b = \delta_c = \arg \left[ a_3 + a_4 + a_5 - \frac{1}{2}(a_7 + a_9 + a_{10}) \right] \equiv \delta. \quad (31) \]
Thus in the SM, the amplitudes $a$, $b$ and $c$ have the same strong and vanishing weak phases. Therefore, all the CP violating parameters $C_{1-6}$ in Eq. (18) are identically zero in the SM. So a nonzero observation of CP violation, in these observables, is a clear signal of new physics.

4 Contribution from the VLDQ model

Now we consider the model with an additional vector-like down quark $[25]$. It is a simple model beyond the SM with an enlarged matter sector with an additional vectorlike down quark $D_4$. The most interesting effects in this model concern CP asymmetries in neutral $B$ decays into final CP eigenstates. At a more phenomenological level, models with isosinglet quarks provide the simplest self-consistent framework to study deviations of $3 \times 3$ unitarity of the CKM matrix as well as allow flavor changing neutral currents at the tree level. The presence of an additional down quark implies a $4 \times 4$ matrix $V_{i\alpha} (i = u, c, t, 4, \alpha = d, s, b, b')$, diagonalizing the down quark mass matrix. For our purpose, the relevant information for the low energy physics is encoded in the extended mixing matrix. The charged currents are unchanged except that the $V_{CKM}$ is now the $3 \times 4$ upper submatrix of $V$. However, the distinctive feature of this model is that the FCNC enters neutral current Lagrangian of the left handed down-quarks:

$$L_Z = \frac{g}{2 \cos \theta_W} \left[ \bar{u}_{Li} \gamma^\mu u_{Li} - \bar{d}_{L\alpha} U_{\alpha\beta} \gamma^\mu d_{L\beta} - 2 \sin^2 \theta_W J_{\mu_{em}}^\mu \right] Z_\mu, \quad (32)$$

with

$$U_{\alpha\beta} = \sum_{i=u,c,t} V_{i\alpha} V_{i\beta} = \delta_{\alpha\beta} - V_{4\alpha} V_{4\beta}, \quad (33)$$

where $U$ is the neutral current mixing matrix for the down sector, which is given above. As $V$ is not unitary, $U \neq 1$. In particular its nondiagonal elements do not vanish:

$$U_{\alpha\beta} = -V_{4\alpha} V_{4\beta} \neq 0 \quad \text{for} \quad \alpha \neq \beta. \quad (34)$$

Since the various $U_{\alpha\beta}$ are nonvanishing, they would signal new physics and the presence of the FCNC at the tree level, and this can substantially modify the predictions for CP asymmetries. The new element $U_{sb}$ which is relevant to our study is given as

$$U_{sb} = V_{us} V_{ub} + V_{cs} V_{cb} + V_{ts} V_{tb}. \quad (35)$$

The decay mode $B^0 \rightarrow \phi K^*$ receives new contributions both from the color allowed as well as the color suppressed $Z$-mediated FCNC transitions. The new additional operators are given as

$$O_1^{Z-FCNC} = [\bar{s}_\alpha \gamma^\mu (1 - \gamma_5) b_\alpha] [\bar{s}_\beta \gamma^\mu (C_V^\ast - C_A^\ast \gamma_5) s_\beta],$$

$$O_2^{Z-FCNC} = [\bar{s}_\beta \gamma^\mu (1 - \gamma_5) b_\alpha] [\bar{s}_\alpha \gamma^\mu (C_V^\ast - C_A^\ast \gamma_5) s_\beta], \quad (36)$$
where \( C_V^s \) and \( C_A^s \) are the vector and axial vector \( Zs\bar{s} \) couplings. Using the Fierz transformation and the identity \( (C_V^s - C_A^s)\gamma_5 = [(C_V^s + C_A^s)(1 - \gamma_5) + (C_V^s - C_A^s)(1 + \gamma_5)]/2 \) as done in Ref. [9] for \( B \to \phi K_S \) mode, the invariant amplitudes \( a, b, \) and \( c \) are given in the factorization approximation as

\[
\begin{align*}
    a_{NP} &= i \frac{G_F}{\sqrt{2}} U_{sb} 2(C_V^s + C_A^s) f_\phi m_\phi (m_B + m_{K^*}) A_1^{B \to K^* (m_\phi^2)}, \\
    b_{NP} &= -i \frac{G_F}{\sqrt{2}} U_{sb} 2(C_V^s + C_A^s) f_\phi m_\phi \left( \frac{2m_{K^*} m_\phi}{m_B + m_{K^*}} \right) A_2^{B \to K^* (m_\phi^2)}, \\
    c_{NP} &= -i \frac{G_F}{\sqrt{2}} U_{sb} 2(C_V^s + C_A^s) f_\phi m_\phi \left( \frac{2m_{K^*} m_\phi}{m_B + m_{K^*}} \right) V^{B \to K^* (m_\phi^2)}.
\end{align*}
\]

The values for \( C_V^s \) and \( C_A^s \) are taken as

\[
C_V^s = -\frac{1}{2} + \frac{2}{3} \sin^2 \theta_W, \quad C_A^s = -\frac{1}{2}.
\]

Now using \( \sin^2 \theta_W = 0.23 \) and the value of \( U_{bs} \) as

\[
|U_{bs}| \simeq 1 \times 10^{-3},
\]

we find

\[
r \equiv r_{a,b,c} \simeq 0.6.
\]

The relative strong and weak phases in this model turn out to be same as all the amplitudes receive the same contribution from new physics effects. Thus we consider \( \delta_a^n = \delta_b^n = \delta_c^n = \delta^n \) and \( \varphi_a^n = \varphi_b^n = \varphi_c^n = \varphi^n \) in our analysis. The branching ratio turns out to be

\[
Br(\bar{B}^0 \to \phi K^{*0}) = Br^{SM} (1 + r^2 + 2r \cos \phi_{NP}),
\]

where \( \phi_{NP} = (\delta^n + \varphi^n) \) and \( Br^{SM} \) denotes the branching ratio in the SM. Now if we plot (Fig-1) the branching ratio vs. \( \phi_{NP} \), we see that the observed branching ratio can be easily accomodated in this model. However, it should be noted that, since new physics contributions to all the three amplitudes \( a, b \) and \( c \) are identical, the values of the normalized polarization amplitudes will remain same as their SM values.

The CP violating observables are obtained from Eq. (20) as

\[
\begin{align*}
    C_1 &= -4 \left[ x|a| + (x^2 - 1)|b| \right]^2 r \sin \delta^n \sin \varphi^n, \\
    C_2 &= -8|a|^2 r \sin \delta^n \sin \varphi^n, \\
    C_3 &= -8(x^2 - 1)|c|^2 r \sin \delta^n \sin \varphi^n, \\
    C_4 &= 4\sqrt{2} \left[ |a|^2 x + (x^2 - 1)|a| |b| \right] r \sin \delta^n \sin \varphi^n, \\
    C_5 &= 0, \\
    C_6 &= 0.
\end{align*}
\]
From the above expressions it can be noted that new physics effects from VLDQ model predict nonzero values for the CP violating parameters $C_{(1-4)}$. Thus, observation of the non-vanishing CP asymmetries implies, in general, the new physics interaction should be of $(V - A)(V - A)$ form, as in the VLDQ model. However, in order to be different from zero, the CP violating parameters $C_{(1-4)}$ require the presence of nonzero relative strong phases $\delta^n$. So in case, these relative strong phases turn out to be zero or too small then the asymmetries in (42) could be too small to be observed experimentally, even in the presence of new physics.

5 Contribution from the R-Parity violating supersymmetric model

We now analyze the decay mode in minimal supersymmetric model with R-parity violation [26]. In the supersymmetric models there may be interactions which violate the baryon number $B$ and the lepton number $L$ generically. The simultaneous presence of both $L$ and $B$ number violating operators induce rapid proton decay, which may contradict strict experimental bound. In order to keep the proton lifetime within experimental limit, one needs to impose additional symmetry beyond those of the SM gauge symmetry. This is to force the unwanted baryon and lepton number violating interactions to vanish. In most cases this has been done by imposing a discrete symmetry called R-parity, defined as, $R_p = (-1)^{(3B+L+2S)}$, where $S$ is the intrinsic spin of the particles. Thus the $R$-parity can be used to distinguish the particle ($R_p = +1$) from its superpartner ($R_p = -1$). This symmetry not only forbids rapid proton decay but also renders the stability of the lightest supersymmetric particle (LSP).
However, this symmetry is ad hoc in nature. There is no theoretical arguments in support of this discrete symmetry. Hence, it is interesting to see the phenomenological consequences of the breaking of R-parity in such a way that either $B$ and $L$ number is violated, both are not simultaneously violated, avoiding rapid proton decays. Extensive studies have been done to look for the direct as well as indirect evidence of R-parity violation from different processes and to put constraints on various R-parity violating couplings. The most general R-parity and Lepton number violating super-potential is given as

$$W_L = \frac{1}{2} \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c,$$

(43)

where, $i, j, k$ are generation indices, $L_i$ and $Q_j$ are $SU(2)$ doublet lepton and quark superfields and $E_k^c$, $D_k^c$ are lepton and down type quark singlet superfields. Further, $\lambda_{ijk}$ is antisymmetric under the interchange of the first two generation indices. Thus the relevant four fermion interaction induced by the R-parity and lepton number violating model is [26]

$$\mathcal{H}_R = \frac{1}{8N_c m_\nu^2} \left[ \left( \lambda'_{i23} \lambda'_{i22} \right) \left( \bar{s}_\gamma \mu (1 - \gamma_5) s \bar{\gamma}_\mu (1 + \gamma_5) b \right) + \left( \lambda'_{i32} \lambda'_{i22} \right) \left( \bar{s}_\gamma \mu (1 + \gamma_5) s \bar{\gamma}_\mu (1 - \gamma_5) b \right) \right].$$

(44)

Using factorization approximation, the amplitudes $a$, $b$ and $c$ in R-parity violating model are obtained as

$$a_{NP} = i f \phi m_\phi (m_B + m_{K^*}) A_1 (m_\phi^2) \left[ \frac{1}{8N_c m_\nu^2} \left( \left( \lambda'_{i32} \lambda'_{i22} \right) - \left( \lambda'_{i23} \lambda'_{i22} \right) \right) \right],$$

$$b_{NP} = -i f \phi m_\phi \left( \frac{2m_\phi m_{K^*}}{m_B + m_{K^*}} \right) A_2 (m_\phi^2) \left[ \frac{1}{8N_c m_\nu^2} \left( \left( \lambda'_{i32} \lambda'_{i22} \right) - \left( \lambda'_{i23} \lambda'_{i22} \right) \right) \right],$$

$$c_{NP} = -i f \phi m_\phi \left( \frac{2m_\phi m_{K^*}}{m_B + m_{K^*}} \right) V (m_\phi^2) \left[ \frac{1}{8N_c m_\nu^2} \left( \left( \lambda'_{i32} \lambda'_{i22} \right) + \left( \lambda'_{i23} \lambda'_{i22} \right) \right) \right],$$

(45)

where the summation over $i = 1, 2, 3$ is implied. Notice, however, that in this case the contributions from NP to the amplitudes $a$ and $b$ are same while the contribution to amplitude $c$ is different. Now considering $r \equiv r_a = r_b$, $\delta^n \equiv \delta^n_a = \delta^n_b$ and $\varphi^n \equiv \varphi^n_a = \varphi^n_b$, the CP violating observables as obtained from (20) are given as

$$C_1 = -4 \left[ x |a| + (x^2 - 1)|b| \right]^2 r \sin \delta^n \sin \varphi^n,$$

$$C_2 = -8 |a|^2 r \sin \delta^n \sin \varphi^n,$$

$$C_3 = -8 (x^2 - 1)|c|^2 r \sin \delta^n \sin \varphi^n,$$

$$C_4 = 4 \sqrt{2} \left[ |a|^2 x + (x^2 - 1)|a| \right] r \sin \delta^n \sin \varphi^n,$$

$$C_5 = -2 \sqrt{2} (x^2 - 1) \left[ x |a| \right] \left[ (x^2 - 1)|b| \right] \left[ \gamma \right]$$

$$\times \left[ r r_c \cos \delta^n \sin \varphi^n + r_c \cos \delta^n \sin \varphi^n - r \cos \delta^n \sin \varphi^n \right],$$

$$C_6 = 4 \sqrt{(x^2 - 1)|a|} \left[ x \right] \left[ r r_c \cos \delta^n \sin \varphi^n + r_c \cos \delta^n \sin \varphi^n - r \cos \delta^n \sin \varphi^n \right].$$

(46)
This set of equations deserves some attention. It should be noted here that the observables $C_{5,6}$ come with cosine of the relative strong phase. Thus, the nonvanishing of $C_{5,6}$ (even in the vanishing relative strong phase limit) imply the presence of new physics effects from R-parity violating model or models with $(V - A)(V + A)$ interaction Hamiltonian. Furthermore, in this case one can get the new physics signal even with vanishing relative strong phases between the SM and NP contributions.

To have an idea about the magnitude of new physics contributions arising from R-parity violating model, we consider the values of R-parity couplings from [27] as

$$\frac{1}{8m_\nu^2} (\lambda'_{i32} \lambda'_{i22}) = ke^{-i\theta} \quad \text{and} \quad \frac{1}{8m_\nu^2} (\lambda'_{i23} \lambda'_{i22}) = -ke^{-i\theta},$$

(47)

where $k$ is the magnitude and $\theta$ is the new weak phase of R-parity violating couplings. For $|\lambda'_{322}| = |\lambda'_{332}| = |\lambda'_{323}| = 0.055$, tan $\theta = 0.52$ and sneutrino mass $m_\nu = 200$ GeV, we obtain for $N_C = 3$,

$$r \equiv r_a = r_b = 0.43 \quad \text{and} \quad r_c = 0.16.$$  

(48)

6 Conclusions

We study the decay process $B^0 \to \phi K^{*0}$, showing that the analysis of the final outgoing particles can be used to detect the presence of new physics. If there happens to be a new physics contribution to its decay amplitude, with a different weak phase, then the standard technique for detecting such NP effects is by measuring direct CP asymmetry parameters. However, the nonvanishing value of these parameters require nonzero relative strong phase between SM and NP amplitudes. So if the strong phases of the SM and NP amplitudes turn out to be equal, the presence of NP cannot be detected. We have shown that this type of new physics can still be detected by performing an angular analysis. In order to achieve the goal of visualising the effect of new physics in this mode, we first obtain six CP violating observables ($C_1 - 6$) from the angular distribution of decay products and show that within the SM, these observables are identically zero. Any nonzero value found in the future study of these observables will indicate the presence of NP. Thereafter, we introduce the generic new physics effect and obtain the modified $C$’s (in the presence of NP) and study in turn two beyond the SM scenarios for the sake of illustration. In fact, we consider the VLDQ model and the RPV supersymmetric model to look for NP.

In the VLDQ model we find that the first four ($C_{1-4}$) observables, out of the six CP violating observables, are nonzero. If found so, this may indicate the nature of the interaction Lagrangian in $B \to \phi K$ to be of the form $(V - A)(V - A)$, which is the case with the VLDQ model. Whereas in the RPV model we find all the six observables to be nonzero. The nonzero values in terms of these observables will indicate the interaction Lagrangian to be of $(V - A)(V + A)$ form.

In summary, we studied the angular distribution analysis of the decay $B \to \phi K^*$ in the SM and beyond it. We obtained six CP violating observables. These are vanishing in the
SM but if found nonvanishing in the future experiments, will definitely indicate the presence of new physics. We have studied two promising models beyond the SM scenarios, where we have shown that these models indeed can have nonzero $C$’s. Since no special technique is required to study them experimentally, and the data are already available, these findings can immediately be studied to look for NP effects in $B \to \phi K^*$ in the currently running $B$ factories. In fact, if these observables are found to be nonzero experimentally then this in turn may eventually lead to the confirmation of the (already existing speculation in $B \to \phi K_S$ decay) new physics in the penguin dominated ($b \to s \bar{s} s$) $B$ decays.

To conclude, irrespective of the fact that whether NP is indeed present in the $B \to \phi K^*$ decay mode or not, the study of the angular distribution will definitely rule out the possibility of the presence of new physics or else establish a strong evidence of it. This angular analysis study in turn deserves an immediate experimental attention.

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