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

Anjan K. Giri
Physics Department, Technion–Israel Institute of Technology, 32000 Haifa, Israel

Rukmani Mohanta
School of Physics, University of Hyderabad, Hyderabad 500046, India

(Received 7 September 2003; published 27 January 2004)

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 make an 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.

DOI: 10.1103/PhysRevD.69.014008 PACS number(s): 13.25.Hw, 11.30.Er, 12.60.Jv

I. INTRODUCTION

The study of B physics provides a great opportunity and an ideal testing ground to obtain 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 evidence of new physics (NP). Recently, the measurement of time dependent CP asymmetries in the $B \to \psi K_S$ 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 [1]

$$\sin(2\beta)_{\psi K_S} = 0.734 \pm 0.054, \tag{1}$$

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 $B \to \psi K_S$ is dominated by the tree level $b \to c\bar{c}s$ 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 on 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 of new physics in the B meson decay amplitudes.

B decays involving the $b \to s\bar{s}s$ transition, such as $B \to \phi K, B \to \eta' K, \phi K^*, \ldots,$ proceed through 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 $B \to \phi K_S$, is estimated to be [2]

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

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

$$\sin(2\beta)_{\phi K_S} = -0.39 \pm 0.41, \tag{3}$$

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

$$\sin(2\beta)_{\phi K_S} = -0.15 \pm 0.33. \tag{4}$$

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 the B system.

Recently, several new physics phenomena have been studied to explain the above discrepancy [6–9]. If new physics effects are indeed present in the decay mode $B \to \phi K_S$, then one can expect to observe similar effects in other modes having the same internal quark structure (in fact, it is this speculation that motivated us to undertake the study in this paper). 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 have a single decay amplitude in the SM. It should be recalled here that in order to observe direct CP violation there should be two interfering decay amplitudes with different strong and weak phases. Observation of direct CP violation in such modes is an unambiguous signal of new physics. However, nonvanishing 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 is present there. However, we still have an opportunity which in turn can help us to find 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 effects emerge, including those that are nonzero even if the strong phase difference vanishes. Therefore, studies of B mesons 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 $\overset{(-)}{B}{}^0 \to \phi \overset{(-)}{K}{}^{*0}$. Recently, the Belle [11] and BaBar [12] Collaborations reported a full angular analysis of $B \to \phi K^*$ decays. The Belle measurements are

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

$$|\hat{A}_0|^2 = 0.43 \pm 0.09 \pm 0.04, \qquad |\hat{A}_\perp|^2 = 0.41 \pm 0.10 \pm 0.04,$$

$$\text{and} \quad |\hat{A}_\parallel|^2 = 1 - |\hat{A}_0|^2 - |\hat{A}_\perp|^2,$$

$$\arg(\hat{A}_\parallel) = -2.57 \pm 0.39 \pm 0.09,$$

$$\arg(\hat{A}_\perp) = 0.48 \pm 0.32 \pm 0.06, \tag{5}$$

and the BaBar data are

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

$$\frac{\Gamma_L}{\Gamma} = 0.65 \pm 0.07 \pm 0.02, \qquad A_{CP} = 0.04 \pm 0.12 \pm 0.02. \tag{6}$$

The average branching ratio of Belle and BaBar measurements is given by

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

From the theoretical point of view, this decay mode has recently been studied within the SM in the framework of QCD factorization [13] and the perturbative QCD (PQCD) approach [14]. Although the branching ratio in the PQCD approach is found to be consistent with the experiment, 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 ϕK_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 vectorlike down quark (VLDQ). It has been shown very recently that these two models can explain the observed 2.7σ discrepancy in the $B \to \phi K_S$ mode [7–9].

The paper is organized as follows. Section II includes a general description of the angular distributions and the observables in $B \to VV$ decays, while in Sec. III we analyze the particular case of $B^0 \to \phi K^{*0}$ in the SM. The new physics effects from the VLDQ model and RPV model are considered in Secs. III and IV, respectively, and in Sec. V we present some concluding remarks.

II. OBSERVABLES AND ANGULAR DISTRIBUTIONS IN $B \to VV$

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

$$\begin{aligned}\frac{1}{\Gamma}\frac{d^3\Gamma}{d\cos\theta_1 d\cos\theta_2 d\psi} &= \frac{9}{8\pi\Gamma}\Big\{ L_1 \cos^2\theta_1 \cos^2\theta_2 + \frac{L_2}{2}\sin^2\theta_1 \sin^2\theta_2 \cos^2\psi \\ &+ \frac{L_3}{2}\sin^2\theta_1\sin^2\theta_2\sin^2\psi + \frac{L_4}{2\sqrt{2}}\sin 2\theta_1 \sin 2\theta_2 \cos\psi \\ &- \frac{L_5}{2\sqrt{2}}\sin 2\theta_1 \sin 2\theta_2 \sin\psi - \frac{L_6}{2}\sin^2\theta_1 \sin^2\theta_2 \sin 2\psi \Big\},\end{aligned} \tag{8}$$

where θ_1 (θ_2) is the angle between the three-momentum of K^+ (K^+) in the ϕ (K^{*0}) rest frame and the three-momentum of ϕ (K^{*0}) in the B rest frame, and in Eq. (8) ψ 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 ϕ and K^{*0} as

$$\begin{aligned} L_1 &= |A_0|^2, & L_4 &= \mathrm{Re}[A_\parallel A_0^*], \\ L_2 &= |A_\parallel|^2, & L_5 &= \mathrm{Im}[A_\perp A_0^*], \\ L_3 &= |A_\perp|^2, & L_6 &= \mathrm{Im}[A_\perp A_\parallel^*]. \end{aligned} \tag{9}$$

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 (ϕ 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]

$$\begin{aligned} H_\lambda &= \langle V_1(\lambda) V_2(\lambda) | \mathcal{H}_{eff} | B^0 \rangle \\ &= \varepsilon^*_{1\mu}(\lambda)\varepsilon^*_{2\nu}(\lambda)\Big[a g^{\mu\nu} + \frac{b}{m_1 m_2} p^\mu p^\nu \\ &+ \frac{ic}{m_1 m_2}\epsilon^{\mu\nu\alpha\beta} p_{1\alpha} p_\beta \Big], \end{aligned} \tag{10}$$

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 ε_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

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

where $x=(p_1\cdot p_2)/m_1m_2=(m_B^2-m_1^2-m_2^2)/(2m_1m_2)$.

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

$$\Gamma=\frac{p_{c.m.}}{8\pi m_B^2}(|H_0|^2+|H_{+1}|^2+|H_{-1}|^2), \tag{12}$$

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

$$\frac{\Gamma_L}{\Gamma_0}=\frac{|H_0|^2}{|H_0|^2+|H_{+1}|^2+|H_{-1}|^2},$$

$$\frac{\Gamma_T}{\Gamma_0}=\frac{|H_{+1}|^2+|H_{-1}|^2}{|H_0|^2+|H_{+1}|^2+|H_{-1}|^2}. \tag{13}$$

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

$$A_\perp=\frac{H_{+1}-H_{-1}}{\sqrt{2}},\qquad A_\parallel=\frac{H_{+1}+H_{-1}}{\sqrt{2}},\qquad A_0=H_0. \tag{14}$$

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

$$\begin{aligned}
L_1&=|xa+(x^2-1)b|^2,\\
L_2&=2|a|^2,\\
L_3&=2(x^2-1)|c|^2,\\
L_4&=-\sqrt{2}[x|a|^2+(x^2-1)\mathrm{Re}(ab^*)],\\
L_5&=-\sqrt{2(x^2-1)}[x\,\mathrm{Im}(a^*c)+(x^2-1)\mathrm{Im}(b^*c)],\\
L_6&=2\sqrt{x^2-1}\,\mathrm{Im}(a^*c).
\end{aligned} \tag{15}$$

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

$$a\to\overline{a},\ b\to\overline{b},\ \text{and}\ c\to-\overline{c}. \tag{16}$$

Here in general, the parameters a, b, and c are complex numbers. One can then write these amplitudes as

$$a=|a|\ e^{i(\delta_a+\varphi_a)}, \tag{17}$$

where δ and φ 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 $B\to\phi K^{*0}$ receives a dominant contribution only from the one-loop $b\to s\overline{s}s$ penguin diagram with a 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 $\overline{a}$ can then be obtained from a by changing the sign of the weak phase. Similar relations as that of Eq. (17) can be written for the parameters b and c.

In our analysis, we will take into account both the decay $B^0\to\phi K^{*0}$ and its CP-conjugate process $\overline{B^0}\to\phi\overline{K}^{*0}$. 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 any of them. These asymmetries can be studied by measuring the coefficients of the first three terms in Eq. (8) for B^0 and $\overline{B}^0$ 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 the last three terms of Eq. (8). Notice, however, that without separating the observables of B^0 and $\overline{B}^0$ decays, the relevant information on CP violation cannot be extracted. Therefore, one must obtain the angular distribution for $B^0\to\phi K^{*0}$ and $\overline{B^0}\to\phi\overline{K}^{*0}$ decays separetely and determine the coefficients L_{1-6} in each case.

Now, in principle, from the angular analysis of $\overset{(-)}{B}{}^0\to\phi\overset{(-)}{K}{}^{*0}$ decays one can measure 12 observables; these are in fact the coefficients L_i and $\overline{L_i}$ with $i=1$ to 6. The CP violating effects in these observables are given by

$$\begin{aligned}
C_1&=L_1-\overline{L_1}=-4x(x^2-1)|a|\ \ |b|\sin\delta_{ab}\sin\varphi_{ab},\\
C_2&=L_2-\overline{L_2}=0,\\
C_3&=L_3-\overline{L_3}=0,\\
C_4&=L_4-\overline{L_4}=2\sqrt{2}(x^2-1)|a|\ \ |b|\sin\delta_{ab}\sin\varphi_{ab},\\
C_5&=L_5+\overline{L_5}=-2\sqrt{2(x^2-1)}|c|[x|a|\cos\delta_{ca}\sin\varphi_{ca}\\
&\qquad+(x^2-1)|b|\cos\delta_{cb}\sin\varphi_{cb}],\\
C_6&=L_6+\overline{L_6}=4\sqrt{(x^2-1)}|a|\ \ |c|\cos\delta_{ca}\sin\varphi_{ca},
\end{aligned} \tag{18}$$

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 final state interaction (FSI) strong phase differences and are especially sensitive to CP violating weak phases.

So far, we have limited our discussion to one 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

$$a_T = a_{SM} + a_{NP} = a_{SM}[1 + r_a e^{i(\delta_a^n + \varphi_a^n)}], \tag{19}$$

where $r_a = |a_{NP}/a_{SM}|$(a_{SM} and a_{NP} correspond to the SM and NP amplitudes) and δ_a^n (φ_a^n) 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

$$\begin{aligned}
C_1 = {}& -4\{x(x^2-1)|a|\;|b|\sin\delta_{ab}\sin\varphi_{ab} + x^2|a|^2 r_a \sin\delta_a^n \sin\varphi_a^n + (x^2-1)^2|b|^2 r_b \sin\delta_b^n \sin\varphi_b^n \\
& + x(x^2-1)|a|\;|b|[r_a\sin(\delta_{ab}+\delta_a^n)\sin(\varphi_{ab}+\varphi_a^n) + r_b\sin(\delta_{ab}+\delta_b^n)\sin(\varphi_{ab}+\varphi_b^n) \\
& + r_a r_b \sin(\delta_{ab}+\delta_{ab}^n)\sin(\varphi_{ab}+\varphi_{ab}^n)]\}, \\
C_2 = {}& -8|a|^2 r_a \sin\delta_a^n \sin\varphi_a^n, \\
C_3 = {}& -8(x^2-1)|c|^2 r_c \sin\delta_c^n \sin\varphi_c^n, \\
C_4 = {}& 2\sqrt{2}\{(x^2-1)|a|\;|b|[\sin\delta_{ab}\sin\varphi_{ab} + r_a\sin(\delta_{ab}+\delta_a^n)\sin(\varphi_{ab}+\varphi_a^n) \\
& + r_b\sin(\delta_{ab}+\delta_b^n)\sin(\varphi_{ab}+\varphi_b^n) + r_a r_b\sin(\delta_{ab}+\delta_{ab}^n)\sin(\varphi_{ab}+\varphi_{ab}^n)] \\
& + 2|a|^2 x r_a \sin\delta_a^n \sin\varphi_a^n\}, \\
C_5 = {}& -2\sqrt{2(x^2-1)}|c|\{x|a|[\cos\delta_{ca}\sin\varphi_{ca} + r_c\cos(\delta_{ca}+\delta_c^n)\sin(\varphi_{ca}+\varphi_c^n) \\
& + r_a\cos(\delta_{ca}-\delta_a^n)\sin(\varphi_{ca}-\varphi_a^n) + r_a r_c\cos(\delta_{ca}+\delta_{ca}^n)\sin(\varphi_{ca}+\varphi_{ca}^n)] \\
& + (x^2-1)|b|[\cos\delta_{cb}\sin\varphi_{cb} + r_c\cos(\delta_{cb}+\delta_c^n)\sin(\varphi_{cb}+\varphi_c^n) \\
& + r_b\cos(\delta_{cb}-\delta_b^n)\sin(\varphi_{cb}-\varphi_b^n) + r_b r_c\cos(\delta_{cb}+\delta_{cb}^n)\sin(\varphi_{cb}+\varphi_{cb}^n)]\}, \\
C_6 = {}& 4\sqrt{(x^2-1)}|a|\;|c|[\cos\delta_{ca}\sin\varphi_{ca} + r_c\cos(\delta_{ca}+\delta_c^n)\sin(\varphi_{ca}+\varphi_c^n) \\
& + r_a\cos(\delta_{ca}-\delta_a^n)\sin(\varphi_{ca}-\varphi_a^n) + r_a r_c\cos(\delta_{ca}+\delta_{ca}^n)\sin(\varphi_{ca}+\varphi_{ca}^n)],
\end{aligned} \tag{20}$$

where $\delta_{ij}^n = \delta_i^n - \delta_j^n$ and $\varphi_{ij}^n = \varphi_i^n - \varphi_j^n$. After obtaining the expressions for the CP violating observables in the presence of new physics, we now proceed to explore specific cases. Before going on to do that, let us first look at the relevant quantities in the SM. A discrepancy, if any, in the SM will necessitate the inclusion of NP to explain the same.

III. SM CONTRIBUTION TO THE AMPLITUDE $B^0 \to \phi K^{*0}$

Let us now focus on the decay $\bar{B}^0 \to \phi \bar{K}^{*0}$. In the SM, this decay process proceeds through the quark level transition $b \to s\bar{s}s$, which is induced by the QCD, electroweak (EW), and magnetic penguins. QCD penguins with the top quark in the loop contribute predominantly to this 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 by

$$H_{eff} = -\frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left(\sum_{j=3}^{10} C_j O_j + C_g O_g \right), \tag{21}$$

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 the 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 $\langle O_i \rangle \equiv \langle \bar{K}^{*0} \phi | O_i | \bar{B}^0 \rangle$.

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

$$\langle O_g\rangle = -\frac{\alpha_s}{4\pi}\frac{m_b}{\sqrt{\langle q^2\rangle}}\left[\langle O_4\rangle+\langle O_6\rangle-\frac{1}{N_C}(\langle O_3\rangle+\langle O_5\rangle)\right]. \tag{22}$$

In the above equation, q^μ is the momentum transferred by the gluon to the $(\bar{s},s)$ pair. The parameter $\langle q^2\rangle$ introduces some 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 $A \equiv \langle \phi \bar{K}^{*0}|H_{eff}|\bar{B}^0\rangle$ of the decay $\bar{B}^0 \to \phi \bar{K}^{*0}$ takes the form

$$A(\bar{B}^0\to\phi\bar{K}^{*0}) = -\frac{G_F}{\sqrt{2}}V_{tb}V_{ts}^*\left[a_3+a_4+a_5-\frac{1}{2}(a_7+a_9+a_{10})\right]X, \tag{23}$$

where

$$X \equiv \langle \phi(\varepsilon_2,p_2)|\bar{s}\gamma_\mu(1-\gamma_5)s|0\rangle \times \langle \bar{K}^{*0}(\varepsilon_1,p_1)|\bar{s}\gamma^\mu(1-\gamma_5)b|\bar{B}^0(p)\rangle \tag{24}$$

stands for the factorizable hadronic matrix element. The coefficients a_i are given by

$$a_{2i-1}=C_{2i-1}^{eff}+\frac{1}{N_c}C_{2i}^{eff}, \qquad a_{2i}=C_{2i}^{eff}+\frac{1}{N_c}C_{2i-1}^{eff}, \tag{25}$$

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]

$$\langle \phi(\varepsilon_2,p_2)|V_\mu|0\rangle = f_\phi\ m_\phi \varepsilon_{2\mu}^*,$$

$$\langle \bar{K}^{*0}(\varepsilon_1,p_1)|V_\mu|\bar{B}(p)\rangle = \frac{2}{m_{K*}+m_B}\epsilon_{\mu\nu\alpha\beta}\varepsilon_1^{*\ \nu}p^\alpha p_1^\beta V(q^2),$$

$$\begin{aligned}\langle \bar{K}^{*0}(\varepsilon_1,p_1)|A_\mu|\bar{B}(p)\rangle &= -i\frac{2m_{K*}(\varepsilon_1^*\cdot q)}{q^2}q_\mu A_0(q^2) \\ &\quad -i(m_{K*}+m_B)\left[\varepsilon_{1\mu}^*-\frac{(\varepsilon_1^*\cdot q)}{q^2}\ q_\mu\right]A_1(q^2) \\ &\quad +i\left[(p+p_1)_\mu-\frac{(m_B^2-m_{K*}^2)}{q^2}q_\mu\right]\frac{(\varepsilon_1^*\cdot q)}{m_{K*}+m_B}\ A_2(q^2),\end{aligned} \tag{26}$$

where V_μ and A_μ 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

$$\begin{aligned} a &= iP_{eff}f_\phi m_\phi(m_B+m_{K*})A_1^{B\to K^*}(m_\phi^2), \\ b &= -iP_{eff}f_\phi m_\phi\left(\frac{2\ \ m_{K*}m_\phi}{m_B+m_{K*}}\right)A_2^{B\to K^*}(m_\phi^2), \\ c &= -iP_{eff}f_\phi m_\phi\left(\frac{2m_{K*}m_\phi}{m_B+m_{K*}}\right)V^{B\to K^*}(m_\phi^2), \end{aligned} \tag{27}$$

where

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

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 $V^{B\to K^*}(m_\phi^2)=0.38$, $A_1^{B\to K^*}(m_\phi^2)=A_2^{B\to K^*}(m_\phi^2)=0.34$, and using the ϕ meson decay constant $f_\phi=$ 0.233 GeV and $\tau_{B^0} = 1.542\times10^{-12}$ sec [23], we obtain the branching ratio in the SM as

$$\mathrm{Br}^{SM}(\bar{B}\to\phi\bar{K}^{*0}) = 8.32\times10^{-6}, \tag{29}$$

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

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

$$|\hat{A}_0|^2=0.869, \qquad |\hat{A}_\perp|^2=0.048, \qquad |\hat{A}_\parallel|^2=0.083, \tag{30}$$

which do not agree with the present experimental data [Eq. (5)]. Furthermore, within the SM all three invariant amplitudes a, b, and c have a 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

$$\delta_a=\delta_b=\delta_c=\arg\left[a_3+a_4+a_5-\frac{1}{2}(a_7+a_9+a_{10})\right]\equiv\delta. \tag{31}$$

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.

IV. CONTRIBUTION FROM THE VLDQ MODEL

Now we consider the model with an additional vectorlike 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 3×3 unitarity of the CKM matrix as well as allowing flavor changing neutral currents (FCNCs) at the tree level. The presence of an additional down quark implies a 4×4 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 V_{CKM} is now the 3×4 upper submatrix of V. However, the distinctive feature of this model is that the FCNC enters the neutral current Lagrangian of the left handed down quarks:

$$\mathcal{L}_Z=\frac{g}{2\cos\theta_W}[\overline{u}_{Li}\gamma^\mu u_{Li}-\overline{d}_{L\alpha}U_{\alpha\beta}\gamma^\mu d_{L\beta}-2\sin^2\theta_W J^\mu_{em}]Z_\mu, \tag{32}$$

with

$$U_{\alpha\beta}=\sum_{i=u,c,t}V^\dagger_{\alpha i}V_{i\beta}=\delta_{\alpha\beta}-V^*_{4\alpha}V_{4\beta}, \tag{33}$$

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

$$U_{\alpha\beta}=-V^*_{4\alpha}V_{4\beta}\neq0 \quad \text{for } \alpha\neq\beta. \tag{34}$$

Since the various $U_{\alpha\beta}$ are nonvanishing, they would signal new physics and the presence of FCNCs 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 by

$$U_{sb}=V^*_{us}V_{ub}+V^*_{cs}V_{cb}+V^*_{ts}V_{tb}. \tag{35}$$

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

$$\begin{aligned}O_1^{Z\text{-}FCNC}&=[\overline{s}_\alpha\gamma^\mu(1-\gamma_5)b_\alpha][\overline{s}_\beta\gamma_\mu(C_V^s-C_A^s\gamma_5)s_\beta],\\ O_2^{Z\text{-}FCNC}&=[\overline{s}_\beta\gamma^\mu(1-\gamma_5)b_\alpha][\overline{s}_\alpha\gamma_\mu(C_V^s-C_A^s\gamma_5)s_\beta],\end{aligned} \tag{36}$$

where C_V^s and C_A^s are the vector and axial-vector $Zs\overline{s}$ couplings. Using the Fierz transformation and the identity $(C_V^s-C_A^s\gamma_5)=[(C_V^s+C_A^s)(1-\gamma_5)+(C_V^s-C_A^s)(1+\gamma_5)]/2$, we obtain the matrix elements of the operators $O_{1,2}^{Z\text{-}FCNC}$ as

$$\begin{aligned}\langle\phi\overline{K}^{*0}|O_1^{Z\text{-}FCNC}|\overline{B}^0\rangle&=\left[\frac{4}{3}\,\frac{(C_V^s+C_A^s)}{2}+\frac{(C_V^s-C_A^s)}{2}\right]X,\\ \langle\phi\overline{K}^{*0}|O_2^{Z\text{-}FCNC}|\overline{B}^0\rangle&=\left[\frac{4}{3}\,\frac{(C_V^s+C_A^s)}{2}+\frac{1}{3}\,\frac{(C_V^s-C_A^s)}{2}\right]X,\end{aligned} \tag{37}$$

where X represents the factorized matrix element given by

$$\begin{aligned}X&=\langle\phi(\varepsilon_2,p_2)|\overline{s}\gamma_\mu(1-\gamma_5)s|0\rangle\\ &\quad\times\langle\overline{K}^{*0}(\varepsilon_1,p_1)|\overline{s}\gamma^\mu(1-\gamma_5)b|\overline{B}^0(p)\rangle\\ &=if_\phi m_\phi\Bigg[(\varepsilon_1^*\cdot\varepsilon_2^*)(m_B+m_{K^*})A_1^{B\to K^*}(m_\phi^2)\\ &\quad-(\varepsilon_1^*\cdot p)(\varepsilon_2^*\cdot p)\frac{2A_2^{B\to K^*}(m_\phi^2)}{m_B+m_{K^*}}\\ &\quad-i\epsilon_{\mu\nu\alpha\beta}\varepsilon_2^{*\mu}\varepsilon_1^{*\nu}p^\alpha p_1^\beta\frac{2V^{B\to K^*}(m_\phi^2)}{m_B+m_{K^*}}\Bigg].\end{aligned} \tag{38}$$

The total amplitude in the VLDQ model is

$$A^{VLDQ}(\overline{B}^0\to\overline{K}^{*0}\phi)=\frac{G_F}{\sqrt{2}}U_{sb}\;2\left(C_V^s+\frac{C_A^s}{3}\right)X. \tag{39}$$

Thus from Eqs. (10), (38), and (39), the invariant amplitudes a, b, and c in the VLDQ model can be written in the factorization approximation as

$$\begin{aligned}a_{NP}&=i\,\frac{G_F}{\sqrt{2}}U_{sb}2\left(C_V^s+\frac{C_A^s}{3}\right)f_\phi\, m_\phi(m_B+m_{K^*})A_1^{B\to K^*}(m_\phi^2),\\ b_{NP}&=-i\,\frac{G_F}{\sqrt{2}}U_{sb}2\left(C_V^s+\frac{C_A^s}{3}\right)f_\phi m_\phi\left(\frac{2\;m_{K^*}m_\phi}{m_B+m_{K^*}}\right)\\ &\quad\times A_2^{B\to K^*}(m_\phi^2),\\ c_{NP}&=-i\,\frac{G_F}{\sqrt{2}}U_{sb}2\left(C_V^s+\frac{C_A^s}{3}\right)f_\phi m_\phi\left(\frac{2m_{K^*}m_\phi}{m_B+m_{K^*}}\right)\\ &\quad\times V^{B\to K^*}(m_\phi^2).\end{aligned} \tag{40}$$

The values for C_V^s and C_A^s are taken as

$$C_V^s=-\frac{1}{2}+\frac{2}{3}\sin^2\theta_W, \qquad C_A^s=-\frac{1}{2}. \tag{41}$$

Now, using $\sin^2\theta_W=0.23$ and the value of U_{bs} from Ref. [9] as

$$|U_{bs}|\simeq1\times10^{-3}, \tag{42}$$

we find

$$r\equiv r_{a,b,c}\simeq0.6. \tag{43}$$

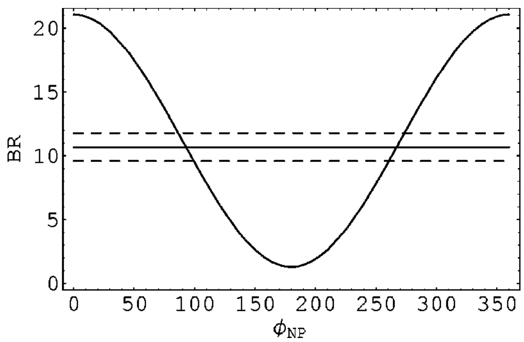

FIG. 1. Branching ratio of $B \to \phi K^{*0}$ process (in units of 10^{-6}) versus the phase ϕ_{NP} (in degrees). The horizontal solid line is the central experimental value, whereas the dashed horizontal lines denote the error limits.

It can be easily seen from Eqs. (39) and (40) that, in the VLDQ model, all three invariant amplitudes a, b, and c receive the same contribution, and therefore all of them have the same strong and weak phases. Thus the relative strong and weak phases between different amplitudes turn out to be zero. However, the relative strong and weak phases between the SM and VLDQ models for each amplitude (i.e., $\delta^n_{a,b,c}$ and $\varphi^n_{a,b,c}$), which are necessary for observing the CP violating asymmetries, are nonzero. Thus we consider $\delta^n_a = \delta^n_b = \delta^n_c = \delta^n$ and $\varphi^n_a = \varphi^n_b = \varphi^n_c = \varphi^n$ in our analysis. The branching ratio turns out to be

$$\mathrm{Br}(\overline{B^0} \to \phi \overline{K}^{*0}) = \mathrm{Br}^{SM}(1 + r^2 + 2r\cos\phi_{NP}), \tag{44}$$

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

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

$$\begin{aligned}
C_1 &= -4[x|a| + (x^2-1)|b|]^2 r \sin\delta^n \sin\varphi^n,\\
C_2 &= -8|a|^2 r \sin\delta^n \sin\varphi^n,\\
C_3 &= -8(x^2-1)|c|^2 r \sin\delta^n \sin\varphi^n,\\
C_4 &= 4\sqrt{2}[|a|^2 x + (x^2-1)|a|\ \ |b|] r \sin\delta^n \sin\varphi^n,\\
C_5 &= 0,\\
C_6 &= 0.
\end{aligned} \tag{45}$$

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, the observation of nonvanishing CP asymmetries in these observables implies, in general, that the new physics interaction should be of the form $\bar{s}\gamma^\mu(1-\gamma_5)s\bar{s}\gamma_\mu(1-\gamma_5)b$, as in the VLDQ model, involving a left handed b quark. New physics contributions from this type of interactions are proportional to SM contributions, which just generate a common weak phase in all amplitudes. However, in order to be different from zero, the CP violating parameters C_{1-4} require the presence of relative nonzero strong phases δ^n. So in case these relative strong phases turn out to be zero or too small, then the asymmetries in Eq. (45) could be too small to be observed experimentally, even in the presence of new physics.

V. CONTRIBUTION FROM THE *R*-PARITY VIOLATING SUPERSYMMETRIC MODEL

We now analyze the decay mode in the minimal supersymmetric model with R-parity violation [26]. In 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 induces rapid proton decay, which may contradict strict experimental bounds. In order to keep the proton lifetime within experimental limits, 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 causes the stability of the lightest supersymmetric particle. However, this symmetry is *ad hoc* in nature. There is no theoretical argument 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 but both are not simultaneously violated, thus avoiding rapid proton decays. Extensive studies have been done to look for direct as well as indirect evidence of R-parity violation in different processes and to put constraints on various R-parity violating couplings. The most general R-parity and lepton number violating superpotential is given by

$$W_{\not{L}} = \frac{1}{2}\lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k, \tag{46}$$

where, i,j,k are generation indices, L_i and Q_j are $SU(2)$ doublet lepton and quark superfields, and E^c_k, D^c_k are lepton and down type quark singlet superfields. Further, λ_{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]

$$\begin{aligned}
\mathcal{H}_{\not{R}} = \frac{1}{8N_c m^2_{\tilde{\nu}}} \{ &(\lambda'^*_{i23}\lambda'_{i22})[\bar{s}\gamma^\mu(1-\gamma_5)s][\bar{s}\gamma_\mu(1+\gamma_5)b]\\
&+ (\lambda'_{i32}\lambda'^*_{i22})[\bar{s}\gamma^\mu(1+\gamma_5)s][\bar{s}\gamma_\mu(1-\gamma_5)b]\}.
\end{aligned} \tag{47}$$

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

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

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

$$c_{NP}=-if_\phi m_\phi\left(\frac{2m_\phi m_{K*}}{m_B+m_{K*}}\right)V(m_\phi^2)\times\left[\frac{1}{8N_c m_{\tilde\nu}^2}[(\lambda'_{i32}\lambda'^*_{i22})+(\lambda'^*_{i23}\lambda'_{i22})]\right], \tag{48}$$

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 the same, while the contribution to the amplitude c is different. Now, considering $r\equiv r_a=r_b$, $\delta^n\equiv\delta_a^n=\delta_b^n$, and $\varphi^n\equiv\varphi_a^n=\varphi_b^n$, the CP violating observables as obtained from Eq. (20) are given by

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

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

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

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

$$C_5=-2\sqrt{2(x^2-1)}[x|a|\ \ |c|+(x^2-1)|b|\ \ |c|]\times[rr_c\cos\delta_{ca}^n\sin\varphi_{ca}^n+r_c\cos\delta_c^n\sin\varphi_c^n-r\cos\delta^n\sin\varphi^n],$$

$$C_6=4\sqrt{(x^2-1)}|a|\ \ |c|[rr_c\cos\delta_{ca}^n\sin\varphi_{ca}^n+r_c\cos\delta_c^n\sin\varphi_c^n-r\cos\delta^n\sin\varphi^n]. \tag{49}$$

This set of equations deserves some attention. It should be noted here that the observables $C_{5,6}$ come with the cosine of the relative strong phase. Thus, the nonvanishing of $C_{5,6}$ (even in the vanishing relative strong phase limit) implies the presence of new physics effects from the R-parity violating model or models with $\bar{s}\gamma^\mu(1-\gamma_5)s\bar{s}\gamma_\mu(1+\gamma_5)b$ interaction Hamiltonian, which involves a right handed b quark. 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 maginitude of new physics contributions arising from R-parity violating model, we consider the values of R-parity couplings from [27] as

$$\frac{1}{8m_{\tilde\nu}^2}(\lambda'_{i32}\lambda'^*_{i22})=ke^{-i\theta}\qquad\text{and}\qquad\frac{1}{8m_{\tilde\nu}^2}(\lambda'^*_{i23}\lambda'_{i22})=-ke^{i\theta}, \tag{50}$$

where k is the magnitude and θ 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 $m_{\tilde\nu}=200$ GeV, we obtain for $N_C=3$

$$r\equiv r_a=r_b=0.43\qquad\text{and}\qquad r_c=0.16. \tag{51}$$

VI. 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 the 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 visualizing 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 scenarios beyond the SM 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 they are found so, this may indicate the nature of the interaction Lagrangian in $B\to\phi^*K$ to be of the form $\sim\bar{s}\gamma^\mu(1-\gamma_5)s\bar{s}\gamma_\mu(1-\gamma_5)b$, which is the case with the VLDQ model. In contrast 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 the form $\sim\bar{s}\gamma^\mu(1-\gamma_5)s\bar{s}\gamma_\mu(1+\gamma_5)b$.

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 future experiments, will definitely indicate the presence of new physics. We have studied two promising models beyond the SM scenario, and 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 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 whether or not NP is indeed present in the $B \to \phi K^*$ decay mode, the study of the angular distribution will definitely rule out the possibility of the presence of new physics or else establish strong evidence of it. This angular analysis study in turn deserves immediate experimental attention.

ACKNOWLEDGMENT

The work of R.M. was supported in part by the Department of Science and Technology, Government of India through Grant No. SR/FTP/PS-50/2001.

[1] Y. Nir, in Proceedings of the ICHEP, Amsterdam, 2002 [Nucl. Phys. B (Proc. Suppl.) **117**, 111 (2003)].
[2] Y. Grossman and M. P. Worah, Phys. Lett. B **395**, 241 (1997); Y. Grossman, G. Isidori, and M. Worah, Phys. Rev. D **58**, 057504 (1997).
[3] Belle Collaboration, K. Abe *et al.*, hep-ex/0207098.
[4] BaBar Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **89**, 201802 (2002).
[5] Belle Collaboration, K. Abe *et al.*, Phys. Rev. Lett. **91**, 261602 (2003); T. Browder, talk presented at the XXI International Symposium on Lepton Photon Interactions at High Energies, 2003.
[6] G. Barenboim, J. Bernabeu, and M. Raidal, Phys. Rev. Lett. **80**, 4625 (1998); M. Raidal, *ibid.* **89**, 231803 (2002); M. Ciuchini and L. Silverstini, *ibid.* **89**, 231802 (2002); E. Lunghi and D. Wyler, Phys. Lett. B **521**, 320 (2001); S. Khalil and E. Kou, Phys. Rev. D **67**, 055009 (2003); G. L. Kane, P. Ko, H. Yang, C. Kolda, J.-H. Park, and L. T. Yang, Phys. Rev. Lett. **90**, 141803 (2003); K. Agashe and C. D. Carone, Phys. Rev. D **68**, 035017 (2003); C.-W. Chiang and J. L. Rosner, *ibid.* **68**, 014007 (2003).
[7] A. Datta, Phys. Rev. D **66**, 071702(R) (2002).
[8] G. Hiller, Phys. Rev. D **66**, 071502(R) (2002).
[9] A. K. Giri and R. Mohanta, Phys. Rev. D **68**, 014020 (2003).
[10] D. London, N. Sinha, and R. Sinha, hep-ph/0304230.
[11] Belle Collaboration. K.-F. Chen *et al.*, Phys. Rev. Lett. **91**, 201801 (2003).
[12] BaBar Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **91**, 171802 (2003).
[13] H.-Y. Cheng and K.-C. Yang, Phys. Lett. B **511**, 40 (2001).
[14] C.-H. Chen, Y.-Y. Keum, and H.-n. Li, Phys. Rev. D **66**, 054013 (2002).
[15] C. W. Chiang and L. Wolfenstein, Phys. Rev. D **61**, 074031 (2000).
[16] G. Kramer and W.F. Palmer, Phys. Rev. D **45**, 193 (1992); G. Kramer, W.F. Palmer, and H. Simma, Nucl. Phys. **B428**, 77 (1994).
[17] A. J. Buras and R. Fleischer, in *Heavy Flavours II*, edited by A. J. Buras and M. Lindner (World Scientific, Singapore, 1998), p. 65.
[18] G. Buchalla, A.J. Buras, and M. Lautenbacher, Rev. Mod. Phys. **68**, 1125 (1996).
[19] A. Ali, G. Kramer, and C.-D. Lü, Phys. Rev. D **58**, 094009 (1998); A. Ali and C. Greub, *ibid.* **57**, 2996 (1998).
[20] G. Barenboim, J. Bernabeu, J. Matias, and M. Raidal, Phys. Rev. D **60**, 016003 (1999).
[21] N. G. Deshpande and J. Trampetic, Phys. Rev. D **41**, 2926 (1990); H. Simma and D. Wyler, Phys. Lett. B **272**, 395 (1991); J.-M. Gerard and W. S. Hou, Phys. Rev. D **43**, 2909 (1991); Phys. Lett. B **253**, 478 (1991).
[22] M. Wirbel, M. Bauer, and B. Stech, Z. Phys. C **29**, 637 (1985).
[23] Particle Data Group, K. Hagiwara *et al.*, Phys. Rev. D **66**, 010001 (2002).
[24] M. Bander, D. Silverman, and A. Soni, Phys. Rev. Lett. **43**, 242 (1979).
[25] Y. Grossman, Y. Nir, and R. Rattazzi, in *Heavy Flavours II* [17], p. 755.
[26] D. Guetta, Phys. Rev. D **58**, 116008 (1998).
[27] B. Dutta, C. S. Kim, and S. Oh, Phys. Rev. Lett. **90**, 011801 (2003).