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The rare $\bar{B}_d^0 \to \phi\gamma$ decays in the standard model and as a probe of R-parity violation

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Abstract. We present a first study of the rare annihilation decay $\bar{B}_d^0 \to \phi\gamma$ in the standard model. Using the QCD factorization formalism, we find $\mathcal{B}(\bar{B}_d^0 \to \phi\gamma) = 3.6 \times 10^{-12}$. The smallness of the decay rate in the standard model makes the decay a sensitive probe of new physics contributions. As an example, we calculate the effects of R-parity violating couplings. Within the available upper bounds for $|\lambda''_{i23}\lambda''^{*}_{i12}|$ and $|\lambda'_{i32}\lambda'^{*}_{i12}|$, $\mathcal{B}(\bar{B}_d^0 \to \phi\gamma)$ could be enhanced to the order of $10^{-9} \sim 10^{-8}$, which might be accessible at LHCB, B-TeV and the planned super high luminosity B factories at KEK and SLAC.

1 Introduction

It is known that flavor changing neutral currents (FCNC) induced rare B decays are very sensitive probes of new physics. The GIM suppression of the FCNC amplitude is absent in many new physics scenarios beyond the standard model (SM), which could give a large enhancement of FCNC processes over the SM predictions. To search such a kind of signals is one of the most important goals of the B projects BaBar, Belle, BTeV, and LHC-B. On the other hand, rare B decays also serve as a laboratory for hadronic dynamics. Due to our poor knowledge of nonperturbative QCD, predictions for many interesting decays are always polluted by uncomfortable large uncertainties, which have hindered us very much in extracting weak interaction information precisely from the available measurements. The well known example is two-body charmless B decays. It would be of great interest to explore rare B decays which are induced by FCNC currents as well as involve few hadronic parameters.

To this end, we will study the pure penguin annihilation decay $\bar{B}_d^0 \to \phi\gamma$. Experimentally, $\bar{B}_d^0 \to \phi\gamma$ is very easy to be identified through the decay chain $\bar{B}_d^0 \to \phi\gamma \to (K^-K^+)\gamma$, i.e., two charge tracks and one energetic photon, and the detecting efficiency should be high. However, if the decay is too rare, it would be very difficult to pick out the signals of the decay from its background, which comes from continuum ($e^+e^- \to q\bar{q}$ with $q = u, d, s$) events with high energy photons originating from initial state radiation or $e^+e^- \to (\pi^0\eta)X$ with $\pi^0\eta \to \gamma\gamma$ [1]. The CLEO Collaboration has performed a search for the decay, but found no evidence and put the upper limit $\mathcal{B}(B_d^0 \to \phi\gamma) < 0.33\times 10^{-5}$ at 90% CL. To our best knowledge, there is no realistic theoretical study of $\bar{B}_d^0 \to \phi\gamma$ in the literature. In this paper, we will investigate this decay. In a naive factorization approach, this decay will involve the simple matrix $\langle\phi|\bar{s}\gamma_\mu s|0\rangle$ and the same hadronic matrix element $\langle\gamma|\bar{q}\gamma_\mu(1-\gamma_5)b|\bar{B}_q\rangle$ as the radiative leptonic decay which has been studied in [2–5] within a different framework. Beyond naive factorization, a nonfactorizable contribution should be included. The QCD factorization framework [6], which has been developed recently by Beneke et al., is employed to calculate $\mathcal{O}(\alpha_s)$ nonfactorization contributions arising from exchanging a hard gluon between the two color octet currents $\bar{s}_\alpha\gamma_\mu(1\pm\gamma_5)s_\beta$ and $\bar{d}_\beta\gamma^\mu(1-\gamma_5)b_\alpha$. We find $\mathcal{B}(\bar{B}_d^0 \to \phi\gamma) = 3.6\times 10^{-12}$ in the SM. The decay rate is too small to be observed at the running B factories BaBar and BELLE. Any measurement of the decay at BaBar and BELLE would be evidence of activity of new physics. As an example, we treat it as a probe of R-parity violating couplings (RPV). Within the available lowest upper bound of RPV couplings, it is found that the branching ratio of the decay could be enhanced to $10^{-9} \sim 10^{-8}$, which might be measured at LHC-B, BTeV and the planned super high luminosity B factories at KEK and SLAC.

2 $\bar{B}_d^0 \to \phi\gamma$ in the standard model

The $\bar{B}_d^0 \to \phi\gamma$ decay is illustrated schematically in Fig. 1; it is dominated by the photon radiating from the light quark in the B meson. Obviously, the amplitude of Fig. 1 is suppressed by a power of $\Lambda_{\rm QCD}/m_b$ because the ϕ meson must be transversely polarized and the B meson is heavy. The diagrams with the photon radiating from the heavy b quark and the energetic strange quarks of the ϕ meson are suppressed by a power of $\Lambda^2_{\rm QCD}/m_b^2$, which will be neglected in this paper. The situation is similar to that of the annihilation contributions in $B \to K^*\gamma$ decays [7].

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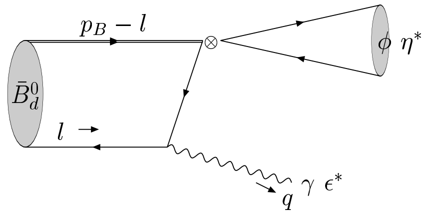

Fig. 1. The leading diagram for $\bar{B}_d^0 \to \phi\gamma$. Radiation of the photon from the remaining three quark lines are further suppressed by a power of $\Lambda_{\rm QCD}/m_b$. The symbol $\otimes$ denotes the insertion of penguin operators O_{3-10}

We begin our study with the effective Hamiltonian in the SM relevant to the decay [8]

$$\mathcal{H}_{\rm eff} = -\frac{4G_{\rm F}}{\sqrt{2}} V_{tb} V_{td}^* \left(\sum_{i=3}^{10} C_i O_i \right) . \tag{1}$$

For convenience, we list below the operators in $\mathcal{H}_{\rm eff}$ for $b \to d s \bar{s}$:

$$\begin{aligned}
O_3 &= \bar{d}_\alpha \gamma^\mu L b_\alpha \cdot \bar{s}_\beta \gamma_\mu L s_\beta \ , \\
O_4 &= \bar{d}_\alpha \gamma^\mu L b_\beta \cdot \bar{s}_\beta \gamma_\mu L s_\alpha \ , \\
O_5 &= \bar{d}_\alpha \gamma^\mu L b_\alpha \cdot \bar{s}_\beta \gamma_\mu R s_\beta \ , \\
O_6 &= \bar{d}_\alpha \gamma^\mu L b_\beta \cdot \bar{s}_\beta \gamma_\mu R s_\alpha \ , \\
O_7 &= \frac{3}{2} \bar{d}_\alpha \gamma^\mu L b_\alpha \cdot e_s \bar{s}_\beta \gamma_\mu R s_\beta \ , \\
O_8 &= \frac{3}{2} \bar{d}_\alpha \gamma^\mu L b_\beta \cdot e_s \bar{s}_\beta \gamma_\mu R s_\alpha \ , \\
O_9 &= \frac{3}{2} \bar{d}_\alpha \gamma^\mu L b_\alpha \cdot e_s \bar{s}_\beta \gamma_\mu L s_\beta \ , \\
O_{10} &= \frac{3}{2} \bar{d}_\alpha \gamma^\mu L b_\beta \cdot e_s \bar{s}_\beta \gamma_\mu L s_\alpha,
\end{aligned} \tag{2}$$

where α and β are the $SU(3)$ color indices and $L = (1 - \gamma_5)/2$, $R = (1 + \gamma_5)/2$. The Wilson coefficients evaluated at the $\mu = m_b$ scale are [8]

$$\begin{aligned}
&C_3 = 0.014,\ C_4 = -0.035,\ C_5 = 0.009, \\
&C_6 = -0.041,\ C_7 = -0.002/137,\ C_8 = 0.054/137, \\
&C_9 = -1.292/137,\ C_{10} = 0.263/137.
\end{aligned} \tag{3}$$

Using the effective Hamiltonian and naive factorization hypothesis, it is easy to write down the amplitude for $\bar{B}_d^0 \to \phi\gamma$:

$$\begin{aligned}
A(\bar{B}_d^0 \to \phi\gamma) &= -\frac{G_{\rm F}}{\sqrt{2}} V_{tb} V_{td}^* \\
&\times \left[\left(C_3 + \frac{C_4}{N_c} + C_5 + \frac{C_6}{N_c} \right) - \frac{1}{2} \left(C_7 + \frac{C_8}{N_c} + C_9 + \frac{C_{10}}{N_c} \right) \right] \\
&\times \sqrt{4\pi\alpha_e} f_\phi m_\phi F_V \\
&\times \left\{ -\epsilon_{\mu\nu\rho\sigma} \eta_\perp^{*\mu} \epsilon_\perp^{*\nu} v^\rho q^\sigma \right. \\
&\left. \quad + \mathrm{i} \left[(\eta_\perp^* \cdot \epsilon_\perp^*)(v \cdot q) - (\eta_\perp^* \cdot q)(v \cdot \epsilon_\perp^*) \right] \right\},
\end{aligned} \tag{4}$$

where $\eta_\perp^*$ and $\epsilon_\perp^*$ are the transverse polarization vectors of ϕ and photon respectively. The form factor F_V is defined by [2–5]

$$\begin{aligned}
&\langle \gamma(\epsilon^*, q) | \bar{d} \gamma_\mu (1 - \gamma_5) b | \bar{B}_d^0 \rangle \\
&= \sqrt{4\pi\alpha_e} \left[-F_V \epsilon_{\mu\nu\rho\sigma} \epsilon^{*\nu} v^\rho q^\sigma + \mathrm{i} F_A (\epsilon_\mu^* q \cdot v - q_\mu v \cdot \epsilon^*) \right] .
\end{aligned} \tag{5}$$

To the leading power of $\mathcal{O}(1/m_b)$, F_V and F_A read [2,3]

$$F_V = F_A = \frac{Q_d f_B M_B}{2\sqrt{2} E_\gamma} \int \mathrm{d}l_+ \frac{\Phi_{B1}(l_+)}{l_+} . \tag{6}$$

The contributions of strong penguin operators arising from the renormalization group evolution from the scale $\mu = M_W$ to $\mu = m_b$ is very small due to the cancellations between them: $C_3 \simeq -C_4/3$ and $C_5 \simeq -C_6/3$. Obviously the amplitude is dominated by an electro-weak penguin (EWP).

Now we can write down the helicity amplitude:

$$\begin{aligned}
\mathcal{M}_{+,+} &= \mathrm{i} \frac{G_{\rm F}}{\sqrt{2}} V_{tb} V_{td}^* \sqrt{4\pi\alpha_e} F_V f_\phi m_\phi M_B \\
&\qquad \times \left[a_3 + a_5 - \frac{1}{2}(a_7 + a_9) \right] ,
\end{aligned} \tag{7}$$

$$\mathcal{M}_{-,-} = 0, \tag{8}$$

where $a_i = C_i + C_{i+1}/N_C$. It is interesting to note that the ϕ meson and the photon in the decay are right-handed polarized in the SM. It is also easy to realize that the decay is very rare because of helicity suppression as well as small V_{td}, f_B and f_ϕ. Using $f_\phi = 254\,\mathrm{MeV}$ [9], $f_B = 180\,\mathrm{MeV}$, $|V_{td}| = 0.008$, $N_C = 3$ and $\lambda_B^{-1} = \int \mathrm{d}l_+ \Phi_{B1}(l_+)/l_+ = (0.35\,\mathrm{GeV})^{-1}$ [3,6], we get

$$\mathcal{B}(\bar{B}_d^0 \to \phi\gamma) = 3.5 \times 10^{-13} . \tag{9}$$

In the above calculations, non-factorizable contributions are neglected. However, the leading non-factorizable diagrams in Fig. 2 should be taken into account. For this purpose, the QCD factorization framework [6] invented recently by Beneke, Buchalla, Neubert and Sachrajda is very suitable. The framework incorporates many important theoretical aspects of QCD like color transparency, the heavy quark limit and hard scattering, which allows us to calculate non-factorizable contributions systematically.

To calculate the non-factorizable diagrams as depicted by Fig. 2, we take the photon and ϕ meson flying along the $n_- = (1,0,0,-1)$ and $n_+ = (1,0,0,1)$ directions respectively. We need the two-particle light-cone projector for B meson and ϕ meson:

$$\begin{aligned}
&\mathcal{M}_{\alpha\beta}^B = \\
&\frac{\mathrm{i}}{4N_c} f_B M_B \left\{ (1 + \not{v}) \gamma_5 \left[\Phi_{B1}(l_+) + \not{n}_- \Phi_{B2}(l_+) \right] \right\}_{\alpha\beta} ,
\end{aligned} \tag{10}$$

$$\begin{aligned}
\mathcal{M}_{\perp\delta\gamma}^\phi &= -\frac{f_\phi^\perp m_\phi}{4N_c} \\
&\times \left\{ \not{\epsilon}_\perp^* g_\perp^{(v)}(u) + \mathrm{i} \epsilon_{\mu\nu\rho\sigma} \epsilon_\perp^{*\nu} n_+^\rho n_-^\sigma \gamma^\mu \gamma_5 \frac{g_\perp^{(a)\prime}(u)}{8} \right\}_{\delta\gamma} ,
\end{aligned} \tag{11}$$

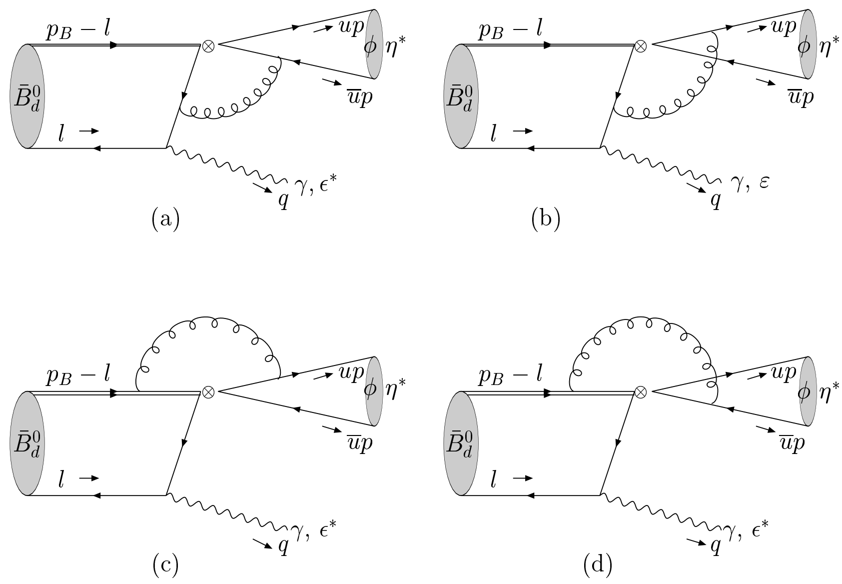

Fig. 2. Non-factorizable diagrams for $\bar{B}_d^0 \to \phi\gamma$. Other diagrams with the photon radiating from the heavy b quark and the energetic quark lines are suppressed

which encode the relevant non-perturbative bound state dynamics of the initial B meson and the final ϕ meson. $\Phi_{B1}(l_+)$ and $\Phi_{B2}(l_+)$ are the leading twist light-cone distribution function of the B meson [10]. $g_\perp^{(v)}(u)$ and $g_\perp^{(a)}(u)$ are the twist-3 distribution amplitudes of the ϕ meson [9], $g_\perp^{(a)\prime}(u) = \mathrm{d}g_\perp^{(a)}(u)/\mathrm{d}u$. The detailed discussions of these projectors could be found in [9–11].

The amplitude for $\bar{B}_d^0 \to \phi\gamma$ can be represented by the schematic formula

$$\begin{aligned}\langle\phi\gamma|\mathcal{H}_{\mathrm{eff}}|B\rangle = &-\frac{G_{\mathrm{F}}}{\sqrt{2}} V_{tb}V_{td}^* \left[(a_3' + a_5') - \frac{1}{2}(a_7' + a_9')\right] \\ &\times \sqrt{4\pi\alpha_e} f_\phi m_\phi F_V \{-\epsilon_{\mu\nu\rho\sigma}\eta_\perp^{*\mu}\epsilon_\perp^{*\nu} v^\rho q^\sigma \\ &+ \mathrm{i}\,[(\eta_\perp^* \cdot \epsilon_\perp^* v\cdot q) - (\eta_\perp^* \cdot q)(v \cdot \epsilon_\perp^*)]\}. \end{aligned} \quad (12)$$

The $\mathcal{O}(\alpha_{\mathrm{s}})$ corrections are summarized in the a_i', which are calculated to be

$$a_3' = a_3 + \frac{\alpha_{\mathrm{s}}}{4\pi}\frac{C_F}{N_C}\frac{f_\phi^\perp}{f_\phi} C_4 F_1, \quad (13)$$

$$a_5' = a_5 + \frac{\alpha_{\mathrm{s}}}{4\pi}\frac{C_F}{N_C}\frac{f_\phi^\perp}{f_\phi} C_6 F_2, \quad (14)$$

$$a_7' = a_7 + \frac{\alpha_{\mathrm{s}}}{4\pi}\frac{C_F}{N_C}\frac{f_\phi^\perp}{f_\phi} C_8 F_2, \quad (15)$$

$$a_9' = a_9 + \frac{\alpha_{\mathrm{s}}}{4\pi}\frac{C_F}{N_C}\frac{f_\phi^\perp}{f_\phi} C_{10} F_1, \quad (16)$$

where $F_{1,2}$ arise from one gluon exchange between the two currents of the color-octet penguin operator $\mathcal{O}_{4,6,8,10}$ as shown by Fig. 2:

$$\begin{aligned} F_1 = &\int_0^1 \mathrm{d}u \left(\frac{g_\perp^{(a)\prime}(u)}{4} - g_\perp^{(v)}(u)\right) \\ &\times \left[-14 - 3\mathrm{i}\pi - 12\ln\frac{\mu}{m_b}\right. \\ &\left. + \left(5 + \frac{u}{1-u}\ln u\right) - \frac{\pi^2}{3} + 2\mathrm{Li}_2(\frac{u-1}{u})\right], \end{aligned} \quad (17)$$

$$\begin{aligned} F_2 = &\int_0^1 \mathrm{d}u \left(g_\perp^{(v)}(u) + \frac{g_\perp^{(a)\prime}(u)}{4}\right) \\ &\times \left[-14 - 3\mathrm{i}\pi - 12\ln\frac{\mu}{m_b}\right. \\ &\left. + \left(5 + \frac{u}{1-u}\ln u\right) - \frac{\pi^2}{3} + 2\mathrm{Li}_2(\frac{u-1}{u})\right]. \end{aligned} \quad (18)$$

In the calculation, the $\overline{\mathrm{MS}}$ renormalization scheme is used. We have neglected the small effect of box diagrams and the diagrams with photons radiating from energetic strange quarks, which are further suppressed by $\Lambda_{\mathrm{QCD}}/M_B$. We also have neglected l_+^2 terms entering in the loop calculation which are higher twist effects; in this way, the integral involving $\Phi_{B2}(l_+)$ is absent and the remaining integrals are related to the form factor F_V.

Including $\mathcal{O}(\alpha_{\mathrm{s}})$ contributions, the helicity amplitude is

$$\begin{aligned}\mathcal{M}_{++} &= \mathrm{i}\frac{G_{\mathrm{F}}}{\sqrt{2}} V_{tb}V_{td}^* \sqrt{4\pi\alpha_e} F_V f_\phi m_\phi M_B \\ &\quad \times \left[a_3' + a_5' - \frac{1}{2}(a_7' + a_9')\right], \\ \mathcal{M}_{--} &= 0. \end{aligned} \quad (19)$$

To give numerical results, we take $\mu = m_b$ and $f_\phi^\perp = 215\,\mathrm{MeV}$ [9]. The branching ratio is estimated to be

$$\mathcal{B}(\bar{B}_d^0 \to \phi\gamma) = 3.6 \times 10^{-12}. \quad (20)$$

It indicates that the decay is too rare to be measured at the running B factories BaBar and BELLE. However, the decay may be accessible at LHCB and the planned super high luminosity B factories at KEK and SLAC. Furthermore, it could be enhanced by new physics, and the enhancement might be large enough to be measured at these facilities.

3 $\bar{B}_d^0 \to \phi\gamma$ as a probe of R-parity violation

As an example, we will study the possible enhancement from the minimal super-symmetric standard model (MSSM) with R-parity violations. In MSSM [12], a discrete symmetry called R-parity is invoked to forbid gauge invariant lepton and baryon number violating operators. The R-parity of a particle is given by [13] $R_p = (-1)^{L+2S+3B}$, where L and B are lepton and baryon numbers, and S is the spin. However, there is no deep theoretical motivation for imposing R-parity and it is interesting to explore the phenomenology of R-parity violation [14].

We start our exploration from the R-parity violating superpotential

$$W_{\not R} = \frac{1}{2}\lambda LLE^{\mathrm{c}} + \lambda' LQD^{\mathrm{c}} + \frac{1}{2}\lambda'' U^{\mathrm{c}}D^{\mathrm{c}}D^{\mathrm{c}}. \qquad (21)$$

We are interested in the λ' and λ'' terms since they are relevant to the process $b \to ds\bar{s}$. Writing down all indices explicitly, it reads

$$W_{\not R} = \varepsilon^{ab}\delta^{\alpha\beta}\lambda'_{ijk}L_{ia}Q_{jb\alpha}D^{\mathrm{c}}_{k\beta} + \frac{1}{2}\varepsilon^{\alpha\beta\gamma}\left[\lambda''_{i[jk]}U^{\mathrm{c}}_{i\alpha}D^{\mathrm{c}}_{j\beta}D^{\mathrm{c}}_{k\gamma}\right], \qquad (22)$$

where $U^{\mathrm{c}}_{i\alpha}$, $D^{\mathrm{c}}_{j\beta}$ and $D^{\mathrm{c}}_{k\gamma}$ are the superfields of the right-handed quarks and/or squarks respectively; the superscript c denotes charge conjugation. i, j and k are generation indices and α, β and γ are $SU(3)$ color triplet indices. It follows from the antisymmetry of $\varepsilon^{\alpha\beta\gamma}$ that $\lambda''_{i[jk]}$ is antisymmetric in the last two indices.

It is well known that $W_{\not R}$ could induce many unique phenomena: single sparticle productions at a high energy collider, and lepton and baryon number violation processes. Of course, it will get bounds from the searchings of these phenomena. A known example is the very strong bounds on the R-parity violation couplings from proton decay [15,16]. If proton decays $P \to \pi^0 + e^+, \pi^+ + \bar{\nu}$ and $P \to \pi^+ + \nu$ take place at tree level, one could get $|\lambda'\lambda''| < 10^{-24}$ [16]. It is found that proton decays induced by loop diagrams could also provide strong bounds for all combinations of pair products of the $\not R_p$ couplings, $|\lambda'\lambda''| < 10^{-7} \sim 10^{-9}$ [17]. However, there still survive a number of weakly constrained couplings, which could be found in the recent updated collections in [14, 20]. Some of these weakly constrained couplings might enhance the rare decay $\bar{B}_d^0 \to \phi\gamma$.

In terms of a four components Dirac spinor, from $W_{\not R}$ we can read

$$\mathcal{L}^{\not R}_{\mathrm{eff}} = \frac{1}{2}\varepsilon^{\alpha\beta\gamma}\left[\lambda''_{ijk}\tilde{u}_{Ri\alpha}\left(\bar{d}^{\mathrm{c}}{}_{j\beta}Rd_{k\gamma} - \{j \leftrightarrow k\}\right)\right] + \lambda'_{ijk}\tilde{\nu}_{Li}\bar{d}_kLd_j + \mathrm{h.c.} \qquad (23)$$

From $\mathcal{L}_{\mathrm{eff}}$, we get the effective Hamiltonian for $b \to ds\bar{s}$:

$$\begin{aligned}\mathcal{H}_{\not R} = {}& \frac{1}{m^2_{\tilde{u}_i}}\varepsilon^{\alpha\beta\gamma}\varepsilon^{\alpha\beta'\gamma'} \\ &\times\left[\lambda''_{i23}\lambda''^*_{i12}(\bar{s}^{\mathrm{c}}_\beta Rb_\gamma)(\bar{s}_{\gamma'}Ld^{\mathrm{c}}_{\beta'})\right. \\ &+\lambda''_{i23}\lambda''^*_{i21}(\bar{s}^{\mathrm{c}}_\beta Rb_\gamma)(\bar{d}_{\gamma'}Ls^{\mathrm{c}}_{\beta'}) + \lambda''_{i32}\lambda''^*_{i12}(\bar{b}^{\mathrm{c}}_\beta Rs_\gamma)(\bar{s}_{\gamma'}Ld^{\mathrm{c}}_{\beta'}) \\ &\left.+\lambda''_{i32}\lambda''^*_{i21}(\bar{b}^{\mathrm{c}}_\beta Rs_\gamma)(\bar{d}_{\gamma'}Ls^{\mathrm{c}}_{\beta'})\right] \\ &+\frac{1}{m^2_{\tilde{\nu}_i}}\left[\lambda'_{i31}\lambda'^*_{i22}(\bar{s}_\alpha Rs_\alpha)(\bar{d}_\beta Lb_\beta)\right. \\ &+\lambda'^*_{i13}\lambda'_{i22}(\bar{s}_\alpha Ls_\alpha)(\bar{d}_\beta Rb_\beta) + \lambda'_{i32}\lambda'^*_{i12}(\bar{d}_\alpha Rs_\alpha)(\bar{s}_\beta Lb_\beta) \\ &\left.+\lambda'^*_{i23}\lambda'_{i21}(\bar{d}_\alpha Ls_\alpha)(\bar{s}_\beta Rb_\beta)\right]. \qquad (24)\end{aligned}$$

Contracting $\varepsilon^{\alpha\beta\gamma}\varepsilon^{\alpha\beta'\gamma'}$ and performing Fierz transformations, we get

$$\begin{aligned}\mathcal{H}_{\not R}(b \to ds\bar{s}) = {}& -\frac{2}{m^2_{\tilde{u}_i}}\lambda''_{i23}\lambda''^*_{i12} \\ &\times\left[(\bar{s}_\beta\gamma_\mu Rs_\beta)(\bar{d}_\gamma\gamma^\mu Rb_\gamma) - (\bar{s}_\beta\gamma_\mu Rs_\gamma)(\bar{d}_\gamma\gamma^\mu Rb_\beta)\right] \\ &-\frac{1}{2m^2_{\tilde{\nu}_i}}\left[\lambda'_{i31}\lambda'^*_{i22}(\bar{s}_\alpha\gamma_\mu Lb_\beta)(\bar{d}_\beta\gamma^\mu Rs_\alpha)\right. \\ &+\lambda'^*_{i13}\lambda'_{i22}(\bar{s}_\alpha\gamma_\mu Rb_\beta)(\bar{d}_\beta\gamma^\mu Ls_\alpha) \\ &+\lambda'_{i32}\lambda'^*_{i12}(\bar{d}_\alpha\gamma_\mu Lb_\beta)(\bar{s}_\beta\gamma^\mu Rs_\alpha) \\ &\left.+\lambda'^*_{i23}\lambda'_{i21}(\bar{d}_\alpha\gamma_\mu Rb_\beta)(\bar{s}_\beta\gamma^\mu Ls_\alpha)\right], \qquad (25)\end{aligned}$$

where we have used the relation

$$(\bar{q}^{\mathrm{c}}\gamma_\mu Lq'^{\mathrm{c}}) = -\left(\bar{q'}\gamma_\mu Rq\right). \qquad (26)$$

The effective Hamiltonian is near to the ideal form. Using the renormalization group to run it from the sfermion mass scale $m_{\tilde{f}_i}$ (assumed to be 100 GeV) down to the m_b scale, it reads

$$\begin{aligned}\mathcal{H}_{\not R}(b \to ds\bar{s}) = {}& -\frac{2}{m^2_{\tilde{u}_i}}\eta^{-4/\beta_0}\lambda''_{i23}\lambda''^*_{i12} \\ &\times\left[(\bar{s}_\beta\gamma_\mu Rs_\beta)(\bar{d}_\gamma\gamma^\mu Rb_\gamma) - (\bar{s}_\beta\gamma_\mu Rs_\gamma)(\bar{d}_\gamma\gamma^\mu Rb_\beta)\right] \\ &-\frac{1}{2m^2_{\tilde{\nu}_i}}\eta^{-8/\beta_0}\left[\lambda'_{i31}\lambda'^*_{i22}(\bar{s}_\alpha\gamma_\mu Lb_\beta)(\bar{d}_\beta\gamma^\mu Rs_\alpha)\right. \\ &+\lambda'^*_{i13}\lambda'_{i22}(\bar{s}_\alpha\gamma_\mu Rb_\beta)(\bar{d}_\beta\gamma^\mu Ls_\alpha) \\ &+\lambda'_{i32}\lambda'^*_{i12}(\bar{d}_\alpha\gamma_\mu Lb_\beta)(\bar{s}_\beta\gamma^\mu Rs_\alpha) \\ &\left.+\lambda'^*_{i23}\lambda'_{i21}(\bar{d}_\alpha\gamma_\mu Rb_\beta)(\bar{s}_\beta\gamma^\mu Ls_\alpha)\right], \qquad (27)\end{aligned}$$

with $\eta = \frac{\alpha_{\mathrm{s}}(m_{\tilde{f}_i})}{\alpha_{\mathrm{s}}(m_b)}$ and $\beta_0 = 11 - \frac{2}{3}n_f$.

Now we are ready to write down R-parity violation contributions in $\bar{B}_d^0 \to \phi\gamma$ decays:

$$\begin{aligned}\mathcal{M}^{\not R}(\bar{B}_d^0 \to \phi\gamma) = {}& \sqrt{4\pi\alpha_e}F_V f_\phi m_\phi \\ &\times\left[\mathrm{i}(\eta^*_\perp\cdot\epsilon^*_\perp)(v\cdot q) + \epsilon_{\mu\nu\alpha\beta}\eta^{*\mu}_\perp\epsilon^{*\nu}_\perp v^\alpha q^\beta\right] \\ &\times\left\{\frac{1}{2m^2_{\tilde{u}_i}}\lambda''_{i23}\lambda''^*_{i12}\eta^{-4/\beta_0}\left(1 - \frac{1}{N_C} - \frac{\alpha_{\mathrm{s}}}{4\pi}\frac{C_F}{N_c}F_1\right)\right. \\ &\left.+\frac{1}{8m^2_{\tilde{\nu}_i}}\lambda'_{i21}\lambda'^*_{i23}\eta^{-8/\beta_0}\left(\frac{1}{N_C} + \frac{\alpha_{\mathrm{s}}}{4\pi}\frac{C_F}{N_c}F_2\right)\right\} \\ &-\sqrt{4\pi\alpha_e}F_V f_\phi m_\phi \\ &\times\left[\mathrm{i}(\eta^*_\perp\cdot\epsilon^*_\perp)(v\cdot q) - \epsilon_{\mu\nu\alpha\beta}\eta^{*\mu}_\perp\epsilon^{*\nu}_\perp v^\alpha q^\beta\right]\end{aligned}$$

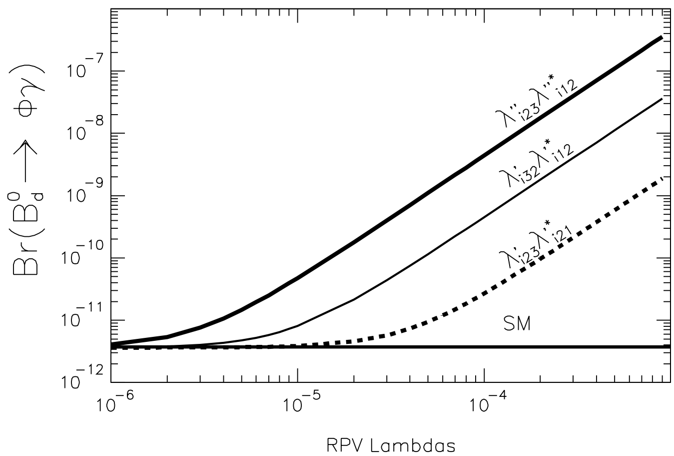

Fig. 3. The branching ratio of $\bar{B}_d^0 \to \phi\gamma$ as a function of R-parity violation couplings $|\lambda''_{i23}\lambda''^*_{i12}|$ (the thick solid curve), $|\lambda'_{i32}\lambda'^*_{i12}|$ (the thin solid curve) and $|\lambda'_{i21}\lambda''^*_{i23}|$ (the dash curve) respectively. The horizontal line is the SM prediction

$$\times \frac{1}{8m^2_{\tilde{\nu}_i}} \lambda'_{i32}\lambda'^*_{i12}\eta^{-8/\beta_0}\left(\frac{1}{N_C} + \frac{\alpha_s}{4\pi}\frac{C_F}{N_c}F_1\right). \quad (28)$$

We note that only u channel squarks and sneutrino mediated terms contribute because of $\langle\gamma|\bar{d}(1\pm\gamma_5)b|\bar{B}_d^0\rangle = 0$. Immediately, we derive

$$\mathcal{M}^{\not R}_{++} = \mathrm{i}M_B\sqrt{4\pi\alpha_e}F_V f_\phi m_\phi \frac{1}{8m^2_{\tilde{\nu}_i}} \lambda'_{i32}\lambda'^*_{i12}\eta^{-8/\beta_0} \times\left(\frac{1}{N_C} + \frac{\alpha_s}{4\pi}\frac{C_F}{N_c}F_1\right), \quad (29)$$

$$\mathcal{M}^{\not R}_{--} = -\mathrm{i}M_B\sqrt{4\pi\alpha_e}F_V f_\phi m_\phi \quad (30)$$
$$\times\left\{\frac{1}{2m^2_{\tilde{u}_i}}\lambda''_{i23}\lambda''^*_{i12}\eta^{-4/\beta_0}\left(1 - \frac{1}{N_C} - \frac{\alpha_s}{4\pi}\frac{C_F}{N_c}F_1\right) + \frac{1}{8m^2_{\tilde{\nu}_i}}\lambda'_{i21}\lambda'^*_{i23}\eta^{-8/\beta_0}\left(\frac{1}{N_C} + \frac{\alpha_s}{4\pi}\frac{C_F}{N_c}F_2\right)\right\}.$$

To present numerical results, we assume that only one sfermion contributes one time and we have a universal mass of 100 GeV for the sfermions $\tilde{u}_{Ri}$. Our results for R-parity violation contributions are summarized in Fig. 3. We note that the decay is very sensitive to R-parity violating couplings. Within the available lowest upper bounds for $|\lambda''_{i23}\lambda''^*_{i21}|$ and $|\lambda'_{i32}\lambda'^*_{i12}|$ in the literature [14,18–20], we have

$$|\lambda''_{i23}\lambda''^*_{i21}| < 6\times10^{-5}\left(\frac{m_{\tilde{u}_{Ri}}}{100}\right)^2,$$
$$|\lambda'_{i32}\lambda'^*_{i12}| < 4\times10^{-4}\left(\frac{m_{\tilde{\nu}_{Li}}}{100}\right)^2; \quad (31)$$

$\mathcal{B}(\bar{B}_d^0 \to \phi\gamma)$ could be enhanced to $10^{-9} \sim 10^{-8}$ which may be inaccessible at BELLE and BaBar. However, it is large enough for LHCb, BTeV and the planned super high luminosity B factories at KEK and SLAC.

4 Conclusion

We have studied the pure penguin radiative annihilation process $\bar{B}_d^0 \to \phi\gamma$ by using QCD factorization for the hadronic dynamics. We find that non-factorizable contributions are larger than factorizable contributions in $\bar{B}_d^0 \to \phi\gamma$ decays. We estimate $\mathcal{B}(\bar{B}_d^0 \to \phi\gamma) = 3.6\times10^{-12}$ in the SM. The smallness of these decays in the SM makes it a sensitive probe of flavor physics beyond the SM. To explore the potential, we have estimated the contribution of RPV couplings to this decay. We have found that the decay $\bar{B}_d^0 \to \phi\gamma$ is very sensitive to the $\lambda'' U^c D^c D^c$ and $\lambda' LQD$ terms in the R-parity violating superpotential. Within the upper limits for $\lambda''_{i23}\lambda''^*_{i21}$ and $\lambda'_{i32}\lambda'^*_{i12}$, it is found that $\mathcal{B}(\bar{B}_d^0 \to \phi\gamma)$ could be enhanced to the order of $10^{-9} \sim 10^{-8}$. We also note that the ϕ meson and the photon are right-handed polarized in the SM, but they can be left-handed polarized in RPV supersymmetry. We find that $\lambda'_{i32}\lambda'^*_{i12}$ RPV couplings contribute to the right-handed polarized magnitude, while $\lambda''_{i23}\lambda''^*_{i12}$ and $\lambda'_{i21}\lambda'^*_{i23}$ RPV couplings are responsible for the left-handed polarized magnitude. Theoretically, measuring the polarization of the photon (or the ϕ meson) can be used to probe the relative strength of the RPV couplings. However, the interesting phenomena faded away by the small branching ratio of the exotic decay. In the literature, there are interesting proposals for probing new physics by measuring the photon polarization in radiative decays $B \to K_i^*\gamma$ [21]. One always needs a large amount of experimental data. For the more exotic decay $\bar{B}_d^0 \to \phi\gamma$, these phenomena will remain academic unless the continuum background could be suppressed efficiently in the data analysis at future B facilities. The interesting decay may be too rare to be accessible at BaBar and Belle. However, the decay rate might be studied by LHCB at CERN, BTeV at Fermilab and the planned super high luminosity B factories at KEK and SLAC to probe new physics.

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References

1. T.E. Coan et al., CLEO Collaboration, Phys. Rev. Lett. **84**, 5283 (2000)
2. G.P. Korchemsky, D. Pirjol, T.M. Yan, Phys. Rev. D **61**, 114510 (2000)
3. S. Descotes-Genon, C.T. Sachrajda, Nucl. Phys. B **650**, 356 (2003), hep-ph/0209216
4. E. Lunghi, D. Pirjol, D. Wyler, Nucl. Phys. B **649**, 349 (2003), hep-ph/0210091
5. P. Ball, E. Kou, JHEP **0304**, 029 (2003), hep-ph/0301135
6. M. Beneke, G. Buchalla, M. Neubert, C.T. Sachrajda, Phys. Rev. Lett. **83**, 1914 (1999); Nucl. Phys. B **579**, 313 (2000)

7. S.W. Bosch, G. Buchalla, Nucl. Phys. B **621**, 459 (2000)
8. For reviews see G. Buchalla, A.J. Buras, M.E. Lautenbacher, Rev. Mod. Phys. **68**, 1125 (1996)
9. P. Ball, V.M. Braun, Y. Koike, K. Tanaka, Nucl. Phys. B **529**, 323 (1998)
10. A.G. Grozin, M. Neubert, Phys. Rev. D **55**, 272 (1997)
11. M. Beneke, F. Feldmann, Nucl. Phys. B **592**, 3 (2001)
12. For reviews see H.P. Nilles, Phys. Rept. **110**, 1 (1984); H.E. Haber, G.L. Kane, Phys. Rept. **117**, 75 (1985); J.F. Gunion, H.E. Haber, Nucl. Phys. B **272**, 1 (1986)
13. G. Farrar, P. Fayet, Phys. Lett. B **76**, 575 (1978)
14. R. Barbier et al., hep-ph/9810232, and references therein
15. S. Weiberg, Phys. Rev. D **26**, 287 (1982); N. Sakai, T. Yanagida, Nucl. Phys. B **197**, 533 (1982)
16. I. Hinchliffe, T. Kaeding, Phys. Rev. D **47**, 279 (1993)
17. A.Y. Smirnov, F. Vissani, Phys. Lett. B **380**, 317 (1996)
18. Shaouly Bar-Shalom, Gad Eilam, Ya-Dong Yang, Phys. Rev. D **67**, 014007 (2003)
19. D.K. Ghosh, X.G. He, H.J. McKellar, J.Q. Shi, J. High Energy Phys. **07**, 067 (2002)
20. C. Allanach, A. Dedes, H.K. Dreiner, Phys. Rev. D **60**, 075014 (1999) and references therein
21. M. Gronau, Y. Grossman, D. Pirjol, A. Ryd, Phys. Rev. Lett. **88**, 051802 (2002); M. Gronau, D. Pirjol, Phys. Rev. D **66**, 054008 (2002)