Constraints on heavy Z' couplings from $\Delta S=2$ $B^- \to K^- K^- \pi^+$ decay

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The heavy Z' boson with family nonuniversal couplings can introduce flavor changing effects. Constraints on nondiagonal Z' couplings coming from the $\mu - e$ conversion in a muonic atom, K^0-$\bar{K}^0$ and B-$\bar{B}$ mixing, ϵ and ϵ'/ϵ CP-violating coefficients have been already established. By using the OPAL upper bound of the branching ratio for the $B^- \to K^- K^- \pi^+$ decay, we indicate additional constraints on the Z' couplings. We comment also on the constraints of Z' couplings coming from the $b \to dd\bar{s}$ transition. The constraint obtained here from the upper bound of the $B^- \to K^- K^- \pi^+$ decay involves a different combination of couplings than those previously presented, but is much weaker.

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In the ongoing search of physics beyond standard model (SM), many extensions have been discussed. Recently, the inclusion of an additional heavy neutral Z' gauge boson has been analyzed in great detail [1]. Heavy neutral bosons Z' are one of the better motivated extensions of the standard model and they appear in grand unified theories, superstring theories and theories with large extra dimensions [1,2]. A most appealing case is offered by the perturbative heterotic string models with supergravity mediated supersymmetry breaking [3]. In this approach the $U(1)'$ and electroweak breaking are both driven by a radiative mechanism.

From the existing direct experimental limits of nonobservation of Z' at Fermilab or indirect limits from precision data at the CERN e^+e^- collider LEP one may deduce [1] that $m_{Z'} > 0$ (500 GeV) and the mixing angle of $Z - Z'$ is rather small, $|\theta| \leqslant 10^{-3}$. Indeed, the Z' mass is predicted in many of the suggested models to be between 0.5 and 1 TeV [1–3]. Moreover, rather stringent limits on the Z' couplings have been determined from various processes such as $\mu - e$ conversion in muonic atoms, K^0-$\bar{K}^0$ and B^0-$\bar{B}^0$ mixing and the ϵ and ϵ'/ϵ parameters of CP violation [1]. On the other hand, arguments have been advanced recently [1,2,4,5] that small apparent deviations from SM could be due to an extra gauge boson Z' of mass between 400 and 800 GeV. These analyses refer to parity violation in atomic cesium [4], various electroweak precision data including the coupling of $b\bar{b}$ pairs [1,2] and the forward-backward charge asymmetry of high-mass lepton pairs produced in p-$\bar{p}$ collisions [5]. Thus it appears that the existence of a Z' in the $\leqslant 1$ TeV region is still a viable possibility and the search for its effect on additional physical processes, or alternatively, further limitation of its couplings is of obvious interest.

The rare B meson decays are very important in current searches of physics beyond SM [6]. The study of the $b \to ss\bar{d}$ transition within SM, and its extensions such as the minimal supersymmetric standard model (MSSM) without and with $\mathcal{R}$ parity violation [7] and two Higgs doublet models [8], have indicated that $\Delta S=2$ rare B meson decays are very good candidates to search for signals of new physics, since the $b \to ss\bar{d}$ transition is very small in the SM having a branching ratio of $10^{-12} - 10^{-11}$ [7]. Among the discussed $\Delta S=2$ decay modes of the B meson [7,9], the $B^- \to K^- K^- \pi^+$ decay provides a good opportunity for investigating physics beyond the SM. This is due to the fact that long-distance effects in this decay were shown [10] to be smaller or comparable to the short-distance box diagram, responsible for this decay in SM [7]. The OPAL Collaboration has recently set an upper bound on the branching ratio of $Br(B^- \to K^- K^- \pi^+) < 8.8 \times 10^{-5}$ [11], which has also been used to obtain new limits on $\mathcal{R}$-parity violating couplings in MSSM.

The extreme smallness of $b \to ss\bar{d}$ in SM leads us to consider in this note the possibility of the occurrence of this transition as a result of Z' exchange. Such a tree diagram mediated by Z', i.e. $b\bar{s} \to Z' \to s\bar{d}$, is indeed allowed in certain theoretical models [1–3,12]. Our aim would then be to calculate the predicted rate of the Z'-induced $b \to ss\bar{d}$ decay; however, as we describe below, the information necessary for such a calculation in the form of upper limits for the couplings (or combination of couplings) involved is not available presently from the previously determined limits on Z' couplings. Therefore, we shall use our calculation of the Z'-induced decay in conjunction with the OPAL result on $B^- \to K^- K^- \pi^+$ in order to obtain further constraints on Z' couplings.

In the analysis of Z' couplings we follow the assumptions of [1], namely the Z' gauge coupling is family nonuniversal as suggested by string models [3] and as a result there are also flavor-changing couplings. We thus write the $\Delta S=2$ effective nonleptonic Lagrangian induced by Z' exchange using the same notation as in Ref. [1]:

$$\mathcal{L} = \frac{4G_F}{\sqrt{2}} y \{ B_{21}^{d_L} B_{23}^{d_L} \bar{s} \gamma_\mu d_L \bar{s} \gamma^\mu b_L + B_{21}^{d_R} B_{23}^{d_R} \bar{s} \gamma_\mu d_R \bar{s} \gamma^\mu b_R + B_{21}^{d_L} B_{23}^{d_R} \bar{s} \gamma_\mu d_L \bar{s} \gamma^\mu b_R + B_{21}^{d_R} B_{23}^{d_L} \bar{s} \gamma_\mu d_R \bar{s} \gamma^\mu b_L \} \quad (1)$$

with

$$y=\left(\frac{g_2}{g_1}\right)^2(\rho_1\sin^2\theta+\rho_2\cos^2\theta) \tag{2}$$

and $g_1=e/\sin\theta_W$, g_2 is the new $U(1)$ gauge coupling, θ is a Z-Z' mixing angle and

$$\rho_i=\frac{M_W^2}{M_i^2\cos^2\theta_W}, \tag{3}$$

where M_i are the masses of the neutral gauge boson eigenstates, θ_W is the electroweak mixing angle and B_{ij} are the unknown couplings.

The experimental results on meson mass splittings Δm_K, Δm_B and Δm_{B_s} constrain the real parts of the squared Z' couplings to quarks [1]:

$$y|\mathrm{Re}[(B_{12}^{d_{R,L}})^2]|<10^{-8},\quad y|\mathrm{Re}[(B_{13}^{d_{R,L}})^2]|<6\times10^{-8},$$
$$y|\mathrm{Re}[(B_{23}^{d_{R,L}})^2]|<2\times10^{-6},\quad y|\mathrm{Re}[(B_{12}^{u_{R,L}})^2]|<10^{-7}, \tag{4}$$

while CP violating parameters in the K meson system bound the imaginary part of the squared Z'-d-s couplings

$$y|\mathrm{Im}[(B_{12}^{d_{R,L}})^2]|<8\times10^{-11}. \tag{5}$$

Other constraints obtained in [2] contain additional couplings (i.e. to leptons or with different coefficients) and are not relevant for the present calculation. It is then more suitable for our purpose to rewrite the limits (4) and (5), related to $B_{i,j}^{d_{R,L}}$ couplings, in the following form:

$$y|(\mathrm{Re}\,B_{12}^{d_{R,L}})^2-(\mathrm{Im}\,B_{12}^{d_{R,L}})^2|<10^{-8},$$
$$y|(\mathrm{Re}\,B_{23}^{d_{R,L}})^2-(\mathrm{Im}\,B_{23}^{d_{R,L}})^2|<2\times10^{-6},$$
$$y|(\mathrm{Re}\,B_{12}^{d_{R,L}})(\mathrm{Im}\,B_{12}^{d_{R,L}})|<4\times10^{-11}. \tag{6}$$

We turn now to the calculation of the $B^-\to K^-K^-\pi^+$ transition via Z' exchange and to explore the limits on Z' couplings provided by the existing experimental upper limit for it [11].

The amplitude for $B^-\to K^-K^-\pi^+$ can be obtained using the effective Lagrangian given in Eq. (1). For the calculation of the matrix elements of the operators appearing in the effective Lagrangian we use the factorization approximation. This requires the knowledge of the matrix elements of the current operators or the density operators. Here we use the standard form factor representation [13,14] of the following matrix elements:

$$\langle P'(p')|\overline{q_j}\gamma^\mu q_i|P(p)\rangle=F_1(q^2)\left(p^\mu+p'^\mu-\frac{m_P^2-m_{P'}^2}{q^2}\times(p^\mu-p'^\mu)\right)+F_0(q^2)\times\frac{m_P^2-m_{P'}^2}{q^2}(p^\mu-p'^\mu), \tag{7}$$

where F_1 and F_0 contain the contribution of vector and scalar states respectively and $q^2=(p-p')^2$. Also, $F_1(0)=F_0(0)$ [14]. For these form factors, one usually assumes pole dominance [14,16]

$$F_1(q^2)=\frac{F_1(0)}{1-\dfrac{q^2}{m_V^2}};\quad F_0(q^2)=\frac{F_0(0)}{1-\dfrac{q^2}{m_S^2}}, \tag{8}$$

where m_V, m_S are the masses of lowest lying vector and scalar resonances. Note that for the transition we consider, the amplitude factorizes in such a way that only the matrix elements of the vector currents contribute. The relevant parameters are taken from [13,15,16] $F_0^{BK}(0)=F_1^{BK}(0)=0.38$, $F_0^{K\pi}(0)=F_1^{K\pi}(0)=0.996$. The masses of the meson poles are $m_{\overline{b}s}(1^-)=5.41$ GeV, $m_{\overline{s}b}(0^+)=5.89$ GeV, $m_{\overline{d}s}(1^-)=0.892$ GeV and $m_{\overline{d}s}(0^+)=1.43$ GeV [13,16]. We introduce $s=(p_B-k_1)^2$, $t=(p_B-k_2)^2=$and $u=(p_B-p_\pi)^2$ and then calculate the matrix element

$$\begin{aligned}&\langle K^-(k_1)K^-(k_2)\pi^+(p_\pi)|(\overline{s}\gamma_\mu d)(\overline{s}\gamma^\mu b)|B^-(p_B)\rangle\\&=F_1^{K\pi}(s)F_1^{BK}(s)\left[m_B^2+m_K^2+2m_\pi^2-s-2t-\frac{m_K^2-m_\pi^2}{s}(m_B^2-m_K^2)\right]+F_0^{K\pi}(s)F_0^{BK}(s)\\&\times\frac{m_K^2-m_\pi^2}{s}(m_B^2-m_K^2)+[s\leftrightarrow t].\end{aligned} \tag{9}$$

When calculating the rate, we denote by $C_{Z'}$ the combination of couplings appearing from Eq. (1) in the decay:

$$C_{Z'}=y[B_{21}^{d_L}B_{23}^{d_L}+B_{21}^{d_R}B_{23}^{d_R}+B_{21}^{d_L}B_{23}^{d_R}+B_{21}^{d_R}B_{23}^{d_L}]. \tag{10}$$

The numerical calculation gives for the branching ratio

$$BR(B^-\to K^-K^-\pi^+)=3.5|C_{Z'}|^2. \tag{11}$$

Combining Eq. (11) with OPAL upper bound for the $B^-\to K^-K^-\pi^+$ decay of 8.8×10^{-5} one finds

$$|C_{Z'}|^2<2.5\times10^{-5}. \tag{12}$$

The limit given in Eq. (12) may be rewritten in a form similar to Eq. (6) as

$$y^2\{(\mathrm{Re}\,B_{21}^{d_L}\,\mathrm{Re}\,B_{23}^{d_L}-\mathrm{Im}\,B_{21}^{d_L}\,\mathrm{Im}\,B_{23}^{d_L}+\mathrm{Re}\,B_{21}^{d_L}\,\mathrm{Re}\,B_{23}^{d_R}-\mathrm{Im}\,B_{21}^{d_L}\,\mathrm{Im}\,B_{23}^{d_R}+\mathrm{Re}\,B_{21}^{d_R}\,\mathrm{Re}\,B_{23}^{d_L}-\mathrm{Im}\,B_{21}^{d_R}\,\mathrm{Im}\,B_{23}^{d_L}+\mathrm{Re}\,B_{21}^{d_R}\,\mathrm{Re}\,B_{23}^{d_R}$$
$$-\mathrm{Im}\,B_{21}^{d_R}\,\mathrm{Im}\,B_{23}^{d_R})^2+(\mathrm{Re}\,B_{21}^{d_L}\,\mathrm{Im}\,B_{23}^{d_L}+\mathrm{Im}\,B_{21}^{d_L}\,\mathrm{Re}\,B_{23}^{d_L}+\mathrm{Re}\,B_{21}^{d_L}\,\mathrm{Im}\,B_{23}^{d_R}+\mathrm{Im}\,B_{21}^{d_L}\,\mathrm{Re}\,B_{23}^{d_R}+\mathrm{Re}\,B_{21}^{d_R}\,\mathrm{Im}\,B_{23}^{d_L}$$
$$+\mathrm{Im}\,B_{21}^{d_R}\,\mathrm{Re}\,B_{23}^{d_L}+\mathrm{Re}\,B_{21}^{d_R}\,\mathrm{Im}\,B_{23}^{d_R}+\mathrm{Im}\,B_{21}^{d_R}\,\mathrm{Re}\,B_{23}^{d_R})^2\}<2.5\times10^{-5}. \tag{13}$$

Inspection of the left-hand side of Eq. (13) reveals that the necessary information needed to present an upper limit for the Z' induced $B^-\to K^-K^-\pi^+$ decay cannot be derived from the relations summarized in Eq. (6), unless we assume some of the couplings to vanish. Hence, Eq. (13) should be viewed as an additional constraint on the Z' couplings, which is not obtainable from the previously considered processes. The existing upper limit on the $B^-\to K^-K^-\pi^+$ branching ratio is rather poor at present and does not allow yet to obtain a constraint on couplings in the same range as in Eq. (6).

Now we briefly comment on possible constraints arising from the $b\to dd\bar{s}$ decay. The effective Lagrangian contributing to this transition is

$$\mathcal{L}=\frac{4G_F}{\sqrt{2}}y\{B_{12}^{d_L}B_{13}^{d_L}\bar{d}\gamma_\mu s_L\bar{d}\gamma^\mu b_L+B_{12}^{d_R}B_{13}^{d_R}\bar{d}\gamma_\mu s_R\bar{d}\gamma^\mu b_R$$
$$+B_{12}^{d_L}B_{13}^{d_R}\bar{d}\gamma_\mu s_L\bar{d}\gamma^\mu b_R+B_{12}^{d_R}B_{13}^{d_L}\bar{d}\gamma_\mu s_R\bar{d}\gamma^\mu b_L\}. \tag{14}$$

Instead of the combination of couplings given in Eq. (10) an experimental bound on the decay rate of $B^-\to\pi^-\pi^-K^+$ will limit the following combination $y[B_{12}^{d_L}B_{13}^{d_L}+B_{12}^{d_R}B_{13}^{d_R}+B_{12}^{d_L}B_{13}^{d_R}+B_{12}^{d_R}B_{13}^{d_L}]$, which can also be expressed in a form similar to Eq. (13).

In concluding, we remark that the rare decays $B^-\to K^-K^-\pi^+$ and $B^-\to\pi^-\pi^-K^+$ can provide additional information on the couplings appearing in the Z' induced nonleptonic Lagrangian, which is complementary to that obtained from mass differences and CP-violating parameters. The new relation obtained here is given in Eq. (13). Its limit is much less stringent than those in Eq. (6), since the considered rare decays are less advantageous presently than the mass differences in obtaining limits for couplings.

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