Lepton Flavor Violation in *B* Decays?

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The LHCb Collaboration's measurement of $R_K = \mathcal{B}(B^+ \to K^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+e^+e^-)$ lies 2.6σ below the Standard Model prediction. Several groups suggest this deficit to result from new lepton nonuniversal interactions of muons. But nonuniversal leptonic interactions imply lepton flavor violation in B decays at rates much larger than are expected in the Standard Model. A simple model shows that these rates could lie just below current limits. An interesting consequence of our model, that $\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm exp}/\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm SM} \cong R_K \cong 0.75$, is compatible with recent measurements of these rates. We stress the importance of searches for lepton flavor violations, especially for $B \to K\mu e$, $K\mu\tau$, and $B_s \to \mu e$, $\mu\tau$.

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The LHCb Collaboration recently measured the ratio of decay rates for $B^+ \to K^+\ell^+\ell^-$ ($\ell = \mu, e$), obtaining [1]

$$R_K \equiv \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} = 0.745^{+0.090}_{-0.074}(\mathrm{stat}) \pm 0.036(\mathrm{syst}). \tag{1}$$

This result is a 2.6σ deficit from the Standard Model (SM) expectation, $R_K = 1 + \mathcal{O}(10^{-4})$ [2–4].

Previous measurements of R_K by the Belle and *BABAR* Collaborations [5,6] had considerably greater uncertainties but were consistent with the SM prediction. The LHCb determination was made for $1 < q^2 = M^2_{\ell\ell} < 6\ \mathrm{GeV}^2$ in order to be well below the radiative tail of the J/ψ. LHCb also measured the $B \to K\mu^+\mu^-$ branching ratio in this q^2 range [7]. The updated result, based on its full Run I data set of 3 fb^{-1}, is [8]

$$\mathcal{B}(B^+ \to K^+\mu^+\mu^-)_{[1,6]} = (1.19 \pm 0.03 \pm 0.06) \times 10^{-7}. \tag{2}$$

The SM prediction [9–11]

$$\mathcal{B}(B^+ \to K^+\mu^+\mu^-)^{\rm SM}_{[1,6]} = (1.75^{+0.60}_{-0.29}) \times 10^{-7} \tag{3}$$

is about 45% higher. Whether this is the cause of the R_K deficit is suggestive, but not certain. Another possibility is a problem in the $B \to Ke^+e^-$ measurement, since LHCb performs better in the $\mu\mu$ than in the ee channel, the latter being hampered by bremsstrahlung and poorer statistics [1]. On the other hand, bremsstrahlung effects largely cancel in the experimental observable, and results for $B \to Ke^+e^-$ are consistent with SM expectations.

The LHCb results for R_K and for anomalies in the $B \to K^*\mu^+\mu^-$ angular distributions (discussed below) have attracted much theoretical attention [12–29]. References [13,16–21,23–25,28] proposed the existence of particles at or above 1 TeV that induce new and *nonuniversal* lepton interactions. Such interactions violate lepton flavor unless the leptons involved are chosen to be mass eigenstates—an unjustifiable act of fine tuning. No known symmetry principle protects lepton flavor conservation in the presence of lepton nonuniversality. Thus, LHCb's reported value of R_K implies, e.g., that $B \to K^{(*)}\mu^\pm e^\mp$ and $B \to K^{(*)}\mu^\pm\tau^\mp$ must occur at rates much higher than would occur in the SM due to tiny neutrino masses. We urge that these and other lepton flavor violations (LFVs) be sought with renewed vigor in LHC Run II and elsewhere.

To illustrate the sort of LFV processes that might be seen in B decays, the limits that currently exist on lepton mixing, and the potential for discovery of LFV, we consider a simple but well-motivated interaction that can account for the known features of the R_K deficit, is consistent with existing limits on LFV, and produces effects that may be observable in LHC Run II. The LHCb data on $B \to K^{(*)}\ell^+\ell^-$ suggest that, despite the detector's superior measurement of muons *vis-à-vis* electrons, the R_K result is due to a ~25% deficit in the muon channel. If so, then LFV is larger for muons than for electrons. This is naturally accounted for by a third-generation interaction of the type that would be expected, e.g., in topcolor models [30]. Furthermore, recent theoretical analyses [13,27,31] indicate that the Hamiltonian for $B \to K^{(*)}\mu^+\mu^-$ (and $B_s \to \mu^+\mu^-$) is best described by the SM and new physics (NP) terms

$$\mathcal{H}_{\rm SM+NP}(\bar{b} \to \bar{s}\mu^+\mu^-) \cong -\frac{4G_F}{\sqrt{2}} V^*_{tb}V_{ts}\frac{\alpha_{\rm EM}(m_b)}{4\pi} \times [\bar{b}_L\gamma^\lambda s_L\bar{\mu}(C^\mu_9\gamma_\lambda + C^\mu_{10}\gamma_\lambda\gamma_5)\mu] + \mathrm{H.c.}, \tag{4}$$

where $C_i^\mu = C_{i,\mathrm{SM}}^\mu + C_{i,\mathrm{NP}}^\mu$ are Wilson coefficients with $C_9^\mu \cong -C_{10}^\mu > 0$. The NP contributions to these coefficients are opposite in sign to the SM contributions, i.e. the lepton current is approximately of $V-A$ form. Therefore, we assume that the third-generation interaction giving rise to the NP part of this Hamiltonian is

$$\mathcal{H}_{\mathrm{NP}} = G\bar{b}'_L\gamma^\lambda b'_L\bar{\tau}'_L\gamma_\lambda\tau'_L, \tag{5}$$

where G is a new-physics Fermi constant ($G = 1/\Lambda_{\mathrm{NP}}^2 \ll G_F$) and the primed fields are the same as appear in the electroweak currents and the Yukawa couplings to the Higgs boson. This sort of interaction would arise from heavy Z' exchange in a topcolor model. (Two other possibilities in this vein are the interactions $G\bar{b}'_L\gamma^\lambda s'_L\bar{\mu}'_L\gamma_\lambda\tau'_L + \mathrm{H.c.}$ or $G\bar{b}'_L\gamma^\lambda s'_L\bar{\tau}'_L\gamma_\lambda\mu'_L + \mathrm{H.c.}$ The first separately conserves the generation numbers N_2 and N_3 while the second conserves $N_2 + N_3$. Also, see the references for other Z' models of the anomalies in $B \to K^{(*)}\ell^+\ell^-$.) These fields are related to the mass-eigenstate (unprimed) fields by unitary matrices U_L^d and U_L^ℓ

$$d'_{L3} \equiv b'_L = \sum_{i=1}^{3} U_{L3i}^d d_{Li}, \qquad \ell'_{L3} \equiv \tau'_L = \sum_{i=1}^{3} U_{L3i}^\ell \ell_{Li}. \tag{6}$$

In particular, the NP interaction responsible for the R_K deficit is

$$\begin{aligned}\mathcal{H}_{\mathrm{NP}}(\bar{b} \to \bar{s}\mu^+\mu^-) \\ = G[U_{L33}^{d*}U_{L32}^d|U_{L32}^\ell|^2\bar{b}_L\gamma^\lambda s_L\bar{\mu}_L\gamma_\lambda\mu_L + \mathrm{H.c.}].\end{aligned} \tag{7}$$

The hierarchy of the Cabibbo-Kobayashi-Maskawa matrix for quarks and the apparent preference of the new physics for muons over electrons suggest that $|U_{L31}^{d,\ell}|^2 \ll |U_{L32}^{d,\ell}|^2 \ll (U_{L33}^{d,\ell})^2 \cong 1$. These expectations can be tested in searches for $B \to K\mu e$ vs $K\mu\tau$. Since the coefficient of the SM term in Eq. (4) is positive, we assume that $GU_{L32}^d < 0$. The reduction of the SM strength in Eq. (4) by this interaction is also supported by the LHCb measurement of the quantity P'_5 in $B^0 \to K^{*0}\mu^+\mu^-$ angular distributions in the low-q^2 region. Integrated over $1.0 < q^2 < 6.0\ \mathrm{GeV}^2$, the P'_5 deficit amounts to 2.5σ [32].

Up to the matrix elements of $\bar{b}_L\gamma^\lambda s_L\bar{\ell}_L\gamma_\lambda\ell_L$, the $B \to K^{(*)}\mu^+\mu^-$ amplitude is

$$\begin{aligned}\beta_{\mathrm{SM}} + \beta_{\mathrm{NP}} &\equiv -\frac{4G_F}{\sqrt{2}}V_{tb}^*V_{ts}\frac{\alpha_{\mathrm{EM}}(m_b)}{4\pi}C_9^e \\ &\quad + \frac{G}{2}U_{L33}^{d*}U_{L32}^d|U_{L32}^\ell|^2 \\ &= -\frac{4G_F}{\sqrt{2}}V_{tb}^*V_{ts}\frac{\alpha_{\mathrm{EM}}(m_b)}{4\pi}C_9^\mu.\end{aligned} \tag{8}$$

Note that the NP contribution to C_9^e is negligible in our model. The LHCb result for R_K in Eq. (1) yields the useful ratio

$$\rho_{\mathrm{NP}} = \frac{\beta_{\mathrm{NP}}}{\beta_{\mathrm{SM}} + \beta_{\mathrm{NP}}} = -0.159^{+0.069}_{-0.070}. \tag{9}$$

Then the branching ratio for $B^+ \to K^+\mu^\pm e^\mp$ (summed over lepton charges) is given by

$$\begin{aligned}\mathcal{B}(B^+ \to K^+\mu^\pm e^\mp) &\cong 2\rho_{\mathrm{NP}}^2\left|\frac{U_{L31}^\ell}{U_{L32}^\ell}\right|^2\mathcal{B}(B^+ \to K^+\mu^+\mu^-) \\ &= (2.16^{+2.54}_{-1.50})\left|\frac{U_{L31}^\ell}{U_{L32}^\ell}\right|^2 \times 10^{-8},\end{aligned} \tag{10}$$

where we used $\mathcal{B}(B^+ \to K^+\mu^+\mu^-) = (4.29 \pm 0.22) \times 10^{-7}$ for the branching ratio integrated over q^2 [8]. The current limit $\mathcal{B}(B^+ \to K^+\mu^\pm e^\mp) < 9.1 \times 10^{-8}$ [33] gives the weak bound

$$|U_{L31}^\ell/U_{L32}^\ell| \lesssim 3.7. \tag{11}$$

Because the primary interaction $\mathcal{H}_{\mathrm{NP}}$ is in the third generation, the decay $B^+ \to K^+\mu^\pm\tau^\mp$ may be more interesting,

$$\mathcal{B}(B^+ \to K^+\mu^\pm\tau^\mp) \cong 2\rho_{\mathrm{NP}}^2\left|\frac{U_{L33}^\ell}{U_{L32}^\ell}\right|^2\mathcal{B}(B^+ \to K^+\mu^+\mu^-). \tag{12}$$

The current limit, $\mathcal{B}(B^+ \to K^+\mu^\pm\tau^\mp) < 4.8 \times 10^{-5}$ [33], gives

$$|U_{L33}^\ell/U_{L32}^\ell| \lesssim 85. \tag{13}$$

This is a crude estimate. It is performed by keeping only the terms proportional to $|C_{9,10}|^2$ in the decay rate. It also neglects the difference in the q^2 range and the phase space for the $\mu\mu$ and $\mu\tau$ modes. These approximations affect $B \to K\tau^+\tau^-$ even more. For this mode, only the weak limit $\mathcal{B}(B \to K\tau^+\tau^-) < 3.3 \times 10^{-3}$ has been set [34].

The B_s decays to a pair of oppositely charged leptons provide an interesting correlation with $B \to K\ell^+\ell^-$. The only observed mode is

$$\begin{aligned}\mathcal{B}(B_s \to \mu^+\mu^-)_{\mathrm{exp}} &= (2.8^{+0.7}_{-0.6}) \times 10^{-9} \\ &= (0.77 \pm 0.20) \times \mathcal{B}(B_s \to \mu^+\mu^-)_{\mathrm{SM}},\end{aligned} \tag{14}$$

where the experimental value is an average of LHCb and CMS measurements with full Run I statistics [35], while the SM value is $\mathcal{B}(B_s \to \mu^+\mu^-)_{\mathrm{SM}} = (3.65 \pm 0.23) \times 10^{-9}$ [36]. The measurement is consistent with the SM prediction but also with $\mathcal{H}_{\mathrm{NP}}$ in Eq. (7) and the value of ρ_{NP} in Eq. (9). Thus, our model implies the triple correlation

$$R_K \cong \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)_{\rm exp}}{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)_{\rm SM}} \cong \frac{\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm exp}}{\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm SM}}. \quad (15)$$

This relation identifies the numerical factor on the right of Eq. (14) with Eq. (1) and stresses the importance of a more accurate measurement of $\mathcal{B}(B_s \to \mu^+\mu^-)$. The only reported LFV limit, $B(B_s \to \mu^\pm e^\mp) < 1.1 \times 10^{-8}$ [37], gives $|U^\ell_{L31}/U^\ell_{L32}| \lesssim 25$, weaker than the bound 3.7 from $B^+ \to K^+\mu e$. We hope that searches for this mode and for $B_s \to \mu\tau$ in LHC Run II can provide much improved limits. (We have not examined the interesting possibility that phases in the off-diagonal $U^{d,\ell}$ matrix elements may induce new CP-violating effects, especially in B_s decays.)

Measurements exist for $\mathcal{B}(B^0 \to K^0\ell^+\ell^-)$ ($\ell = e, \mu$) and $\mathcal{B}(B_s \to \phi\mu^+\mu^-)$. These are comparable to but less precise than $\mathcal{B}(B^+ \to K^+\ell^+\ell^-)$. Similarly, limits on $B^0 \to \ell^+\ell^-$ and the LFV decays $B^0 \to K^{(*)0}\mu e$ and $\ell^\pm\ell'^\mp$, including τ modes, give no more stringent limits than those for B^+ decays. The amplitudes for $B^0 \to \ell^+\ell^-$ and $\ell^\pm\ell'^\mp$ are suppressed by V_{td}/V_{ts} and U^d_{L31}/U^d_{L32} relative to the corresponding B_s decays. (Our interaction $\mathcal{H}_{\rm NP}$, as well as those mentioned earlier, will induce rare LFV decays for kaons. Such a study is worthwhile because of the considerable interest worldwide in experiments with intense beams, but it is beyond the scope of this Letter.)

Finally, the operator

$$\mathcal{H}_{\rm NP}(\mu + d \to d + e) = G|U^d_{L31}|^2 \bar{d}_L\gamma^\lambda d_L(U^{\ell*}_{L31}U^\ell_{L32}\bar{e}_L\gamma_\lambda\mu_L + {\rm H.c.}) \quad (16)$$

induces $\mu \to e$ conversion in nuclei. (Our model Hamiltonian $\mathcal{H}_{\rm NP}$ can also induce $\mu \to e\gamma$. Simply closing up the quark line and emitting a photon from it does not produce the desired operator, $\propto eGm_\mu\bar{e}\sigma^{\lambda\nu}\mu F_{\lambda\nu}$. Virtual exchanges of electroweak or Higgs bosons and/or a mass insertion must occur between the quark and lepton lines to change the muon chirality. We expect that such an operator is too weak to give an interesting limit.) The limit on the strength of this operator from conversion in titanium is (see Table 3.6 in Ref. [38])

$$G|U^d_{L31}|^2|U^{\ell*}_{L32}U^\ell_{L31}| < \frac{4G_F}{\sqrt{2}} \times (8.5 \times 10^{-7}). \quad (17)$$

Using

$$\left|\frac{\beta_{\rm NP}}{\beta_{\rm SM}}\right| = \left|\frac{\pi G U^{d*}_{L33}U^d_{L32}|U^\ell_{L32}|^2}{\sqrt{2}G_F\alpha_{\rm EM}V^*_{tb}V_{ts}C^e_9}\right| \simeq 0.14, \quad (18)$$

together with $|V_{tb}| \simeq 1$, $|U^d_{L32}| \simeq |V_{ts}| \cong 0.043$, $|U^d_{L31}| \simeq |V_{td}| \cong 0.0084$ [33], and $\alpha_{\rm EM}(m_b) = 1/133$, we obtain the weak limit

$$\left|\frac{U^\ell_{L31}}{U^\ell_{L32}}\right| < \frac{75}{|C^e_9|} \cong 18, \quad (19)$$

where $|C^e_9| \cong 4.07$ [39]. The Mu2e experiment at Fermilab is designed to be sensitive to an interaction strength 100 times smaller than that in Eq. (17). Under our assumptions, Mu2e would then be able to probe $|U^\ell_{L31}/U^\ell_{L32}| \gtrsim 0.2$.

Summing up: The interesting new results on $B \to K^{(*)}\mu^+\mu^-$ and R_K from LHCb, if correct, tell us that there are lepton number nonuniversal interactions. Therefore, there must also be lepton-flavor-violating interactions, and there is no known reason these should be very much weaker than the nonuniversal ones. Limits from searches for $B \to K\ell^+\ell'^-$ and $B_s \to \ell^+\ell'^-$ are not far above interesting ranges for LFV mixing-angle parameters. LHCb's results make searches for these and other rare processes well worth pursuing.

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