BRIEF REPORTS

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Lepton polarization asymmetry in rare B decays

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We study the right-left polarization asymmetry for rare B decays into dileptons. With the Wilson coefficients evaluated at next-to-leading order and the top quark mass from Fermilab, we calculate and plot this asymmetry for the e and μ channels.

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Rare dilepton B decays like their radiative counterparts proceed through flavor-changing neutral current diagrams that are absent at the tree level and thus are sensitive to extensions of the standard model [1]. The recent measurement of $B \to X_s\gamma$ by the CLEO group [2] results in a strong constraint on parameters describing extensions of the standard model, especially on charged Higgs parameters. Present searches for rare B decays into final dileptons have set an upper limit within a factor of 3 of the branching ratio predicted by the standard model [3]. We expect that upcoming measurements in the current B facilities and at future B factories will offer more and more information about these leptonic channels. Because of the several sources which can lead to these decays, including even the long-distance contribution from J/ψ and ψ' resonances, the proper method of isolating different effects in the dileptonic channel is to measure a number of kinematic distributions of the final state particles. So far, besides extensive studies about the invariant mass spectrum of dileptons, there is published work on the leptonic forward-backward charge asymmetry [4–7] and the polarization of K^* in the exclusive channel [8]. In this Brief Report, we present our calculations for the leptonic right-left polarization asymmetry in the decay $B \to X_s l^+l^-$ ($l = e$ and μ) within the standard model. We do not consider the $\tau^+\tau^-$ channel here for two reasons: First, the phase space is limited and appreciably reduces the branching fraction; second, the left- and right-handed chiral projections do not quite correspond to helicities for massive leptons, and so the kinematics is rather more complicated.

Let us begin with an effective Hamiltonian relevant to flavor-changing one-loop processes $b \to sl^+l^-$ [9] (s_W denotes $\sin\theta_W$):

$$H_{\rm eff} = \frac{G_F}{\sqrt{2}}\left(\frac{\alpha}{4\pi s_W^2}\right) \times[\bar{s}\Gamma_\mu^A b\,\bar{l}\gamma^\mu(1-\gamma_5)l + \bar{s}\Gamma_\mu^B b\,\bar{l}\gamma^\mu(1+\gamma_5)l], \quad (1)$$

with effective vertices $\Gamma_\mu^{A(B)} = A(B)\gamma_\mu(1-\gamma_5) - im_b s_W^2 F_2 \sigma_{\mu\nu}q^\nu(1+\gamma_5)/q^2$. The F_2 term arises from the *photon penguin* diagram and is necessarily the same for left- and right-handed leptons in order to produce a purely vectorial interaction at the photon end, while the $(1+\gamma_5)$ factor at the quark end is dictated by the handedness of the quarks. The interference between the *leptonic* vector and axial vector parts is responsible for the asymmetry which is the subject of this note. The coefficient functions are given by

$$A = \sum_{q=u,c,t} U_q\, A_q, \quad B = \sum_{q=u,c,t} U_q\, B_q,$$

$$F_2 = \sum_{q=u,c,t} U_q\, F_2^q, \quad (2)$$

in which $U_q = V_{qs}^* V_{qb}$ is the product of the relevant elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix. As long as the u quark is ignored, one has $U_c + U_t = 0$ from unitarity of the CKM matrix. The individual Wilson coefficients A_q, B_q, and F_2^q can be found in Refs. [10–13]. Here we emphasize that the combination $A - B$ is not renormalized under QCD, retains its value at the higher mass scale, and thus is independent of the choice of the lower scale μ. With $\alpha_s(\mu)/\alpha_s(M_W) = 1.75$ and $m_t = 180$ GeV, obtained by averaging the data of Collider Detector at Fermilab (CDF) and D0 groups [14], we have the values of the coefficient functions arising from loops containing the top quark, $A_t = 2.09$, $B_t = -0.126$, and $s_W^2 F_2^t = -0.153$ at next-to-leading order [12,13]. The contribution of resonances such as J/ψ and ψ' to the effective Hamiltonian, Eq. (1), may be taken into account via the usual form of vector-meson dominance [15–17]:

$$A_V = B_V = \frac{16\pi^2}{3}\left(\frac{f_V}{M_V}\right)^2 \frac{a_2 s_W^2}{q^2 - M_V^2 + iM_V\Gamma_V}, \quad (3)$$

where M_V is the mass of the vector intermediate state and Γ_V its full width. The decay constant is defined by $f_V \epsilon_\mu = \langle 0|\bar{c}\gamma_\mu c|V(\epsilon)\rangle$ and will be determined by the measured partial width for decays to lepton pairs. In this work we treat the coupling for the neutral $\bar{b}\bar{s}c\bar{c}$ four-quark operator a_2 as a phenomenological parameter and use the CLEO data $|a_2| = 0.26 \pm 0.03$ [18], which is close to the value determined from a fit to the rate for the semi-inclusive process $B \to X_s J/\psi$ [19]. The choice of a negative a_2 will be made, consistent with a Breit-Wigner phase $\phi = 0$ [20]. Note that the combination $A - B$ still remains unchanged after vector resonant states are included.

Assuming the effective Hamiltonian in Eq. (1) we obtain the differential distribution

$$\frac{1}{\Gamma_{\rm sl}}\frac{d(\Gamma_R - \Gamma_L)}{ds} = \frac{1}{8\pi^2 \tilde{f}_{bc}}\left(\frac{\alpha}{s_W^2}\right)^2 (1-s)^2 \left\{(1+2s)(|B|^2 - |A|^2) + 6\,{\rm Re}[s_W^2 F_2 (B-A)^*]\right\}, \qquad (4)$$

for the right-left asymmetry, in the limit of massless leptons and summing over the spin states of quarks. The asymmetry is normalized to the semileptonic decay rate of the B meson and $\tilde{f}_{bc}$ numerically equals 0.39, upon including the one-loop QCD correction to the semileptonic B decay. Also in Eq. (4) we have measured s in units of m_b^2 so that the squared invariant mass of the dilepton ranges over $0 \le s \le 1$, when the mass of the strange quark is ignored. The right-left asymmetry contains an overall factor $A-B$, just like the forward-backward asymmetry [4–7]; this is because they both are parity-violating effects. The contribution of the Z boson penguin diagram along with the W boson box is larger than that of the photon penguin diagram in the whole range of the leptonic invariant mass, but especially so in the $s \simeq 1$ region. Hence the right-left asymmetry offers an effective manner to probe the Z boson penguin and W boson box diagrams, as well as nonstandard model extensions of them. The asymmetry is proportional to $\Gamma_R - \Gamma_L$ clearly and carries a factor m_b^5. The question arises how to normalize it. A naive choice would be to divide it by $\Gamma_R + \Gamma_L$; however, the latter is largely dominated by the long-distance J/ψ contribution which would render the ratio $(\Gamma_R - \Gamma_L)/(\Gamma_R + \Gamma_L)$ really miniscule and sensitive to the exact value of m_b. It is more sensible and practical as we have done to divide the asymmetry by the semileptonic decay rate of the B meson $\Gamma_{\rm sl}$ which itself contains m_b^5 and thereby eliminates the uncertainty in the bottom quark mass.

We plot the *integrated* right-left asymmetry in the process $B \to X_s l^+ l^-$ in Fig. 1. The top quark effect is the major contribution and we find analytically, for the top quark alone at $s = 1$,

$$\frac{(\Gamma_R - \Gamma_L)_{\rm top}}{\Gamma_{\rm sl}} = \left(\frac{\alpha}{4\pi s_W^2}\right)^2 \frac{B_t - A_t}{\tilde{f}_{bc}}(A_t + B_t + 4 s_W^2 F_2^t), \qquad (5)$$

which takes the value of -4.8×10^{-5} for the stated coefficients. The effects arising from charm quarks, in the forms of continuum and resonance, reduce the magnitude of the asymmetry, especially in the resonant region (the impact of the J/ψ peak is strong compared to the ψ' peak) and both peaks in the figure reflect the real part of Eq. (3) as we range in s. We have checked the dependence on the QCD renormalization parameter: For $\alpha_s(\mu)/\alpha_s(M_W)$ in the range of 1.50–2.00, the asymmetry integrated over the whole range of the invariant mass varies within 17%. Also, the experimental uncertainty due to the top quark mass, ±12 GeV, is 31%, which matches the m_t^2 behavior of the combination $A_t - B_t$. There are a few publications [4–7] which have investigated the forward-backward charge asymmetry, which is another parity-violating phenomenon. Both effects measure the magnitude of the axial vector component of the lepton current $(A - B)$, which interferes with the polar vector component. Near $s = 0$, $\Gamma_{\rm FB}$ is dominated by the interference between the photon penguin and the Z

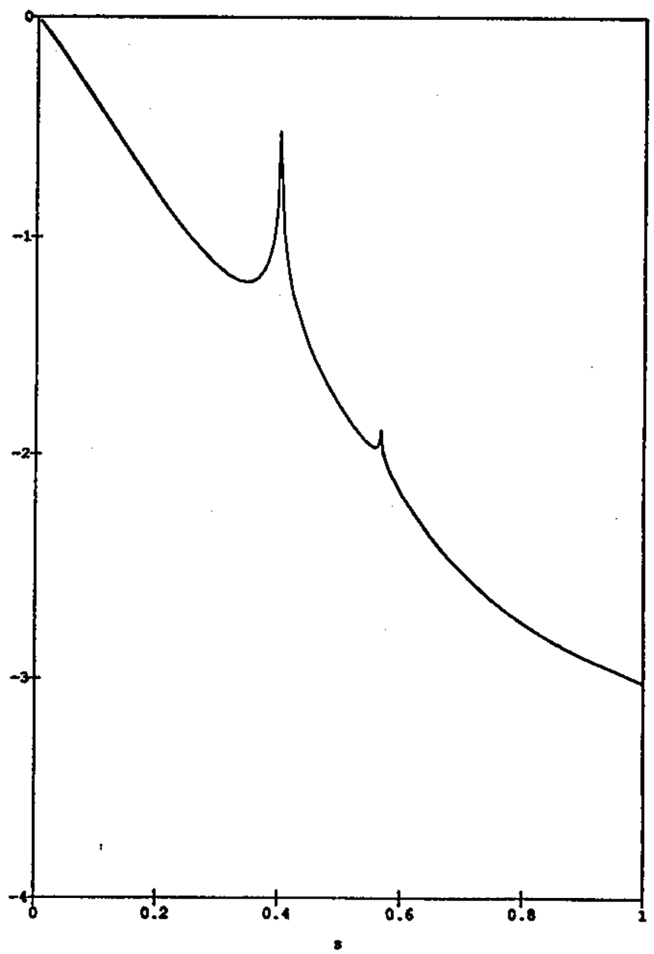

FIG. 1. Integrated right-left polarization asymmetry $\int_0^s d\Gamma_{RL}$ in $B \to X_s\ l^+ l^-$ as a function of s. We take the values $m_t = 180$ GeV, $m_b = 4.9$ GeV, $m_c = 1.5$ GeV, and $\alpha_s(\mu)/\alpha_s(M_W) = 1.75$. The plot is rescaled by the semileptonic decay width of the B meson, multiplied by the factor of 10^5.

boson penguin diagrams along with the W boson box, namely, $(A-B)F_2$; this is not the case for Γ_{RL}. Rather Γ_{RL} is dominated by the the Z boson penguin and the W boson box diagrams over the whole s range, given the magnitudes of A, B, and $s_W^2 F_2$. Another point worth mentioning is that the size of F_2 is determined experimentally by $\Gamma(B \to X_s\gamma)$, and so since the $A-B$ cancels out of the ratio $\Gamma_{RL}/\Gamma_{\rm FB}$, the data for $\Gamma_{RL}\Gamma_{\rm FB}$ provides information about $A+B$, using F_2 as input.

In conclusion, we have calculated the right-left polarization asymmetry in the $B \to X_s l^+ l^-$ within the framework of the standard model and find it is sensitive to the Z boson penguin and W boson box diagrams. The integrated asymmetry is therefore predicted to be about $-3.0\times10^{-5}\Gamma_{\rm sl}$ for the top quark mass of the CDF and D0 groups. (This should be within the reach of the B-meson factories.) Moreover, this value is the same order of magnitude as the decay rate of the μ channel. The reasons for it are twofold. First, the production of left-handed leptons is much larger than that of right-handed ones. Thus as far as Z penguin and W box diagrams are concerned, the difference between rates of the right and left leptons is not far away from the sum of them. As well, there is a logarithm of the small leptonic mass in the decay rate due to the photon penguin diagram, but this cancels out in the asymmetry. (The enhancement of this term is weaker in the μ channel than the e channel.) Hence the right-left polarization asymmetry is small, compared with the rate of e production, but comparable to the μ production rate. We therefore expect that measurements of this asymmetry will detect the loop diagrams containing Z and W bosons and probe nonstandard model extensions. This asymmetry in the μ channel should be readily found via the angular distributions of the decay products in the subsequent μ decays, which depend on the μ polarization. However, for the e channel this may be a little more difficult to test experimentally.

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