Title
CP Noninvariance in the Decays of Heavy Charged Quark Systems

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$=2\Delta N_\nu$ and $g_{AB}=0$ so that we obtain the constraint

$$\Delta N_\nu \lesssim 0.94[\tfrac{4}{11}(N_{\gamma 0}/N_{\gamma d})]^{4/3}. \tag{11}$$

In Table I we also give the limit to ΔN_ν as a function of the decoupling temperature.

If the "new" neutrinos interact superweakly because they couple to a heavier W' $(m_{W'}>m_W)$, the decoupling temperature depends on $m_{W'}$. The cross section for $e^+ + e^- \rightleftarrows \nu' + \bar{\nu}'$ varies as $\sigma' \sim T^2 m_{W'}^{-4}$ and the reaction rate $\Gamma = n_e \langle \sigma' v\rangle \sim T^5 m_{W'}^{-4}$. Since the expansion rate is $t^{-1} \sim T^2$, the decoupling temperature $T_d \sim m_{W'}^{4/3}$. For neutrinos coupled to the W, decoupling is at ≈ 1 MeV so that $T_d\,(\mathrm{MeV}) \approx (m_{W'}/m_W)^{4/3}$.

For example, for $m_{W'} \lesssim 32 m_W$, $T_d \lesssim m_\mu$ and it follows from Table I that at most one "new" two-component neutrino is allowed. Another consequence of the results in Table I is that if the usual left-handed neutrinos have right-handed counterparts, the right-handed neutrinos must decouple when $T_d > T_c \gtrsim 0.2$ GeV; this suggests that $m_{W_R} \gtrsim 53 m_{W_L}$.

Similar constraints follow for other new particles. For example, for gravitinos, $N_A = (\Delta N_\nu)_{\max} \approx 20$ and, for gravitons, $N_A = \frac{7}{8}(\Delta N_\nu)_{\max} \approx 17$.

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[1]G. Steigman, D. N. Schramm, and J. E. Gunn, Phys. Lett. 66B, 202 1977.

[2]P. Hut, Phys. Lett. 69B, 85 1977.

[3]S. Weinberg, in *Neutrinos—1978*, edited by Earle C. Fowler (Purdue Univ. Press, W. Lafayette, Ind. 1978).

[4]J. Yang, D. N. Schramm, G. Steigman, and R. T. Rood, Astrophys. J. 227, 697 1979. In this paper the limit to the number of full-strength neutrinos was quoted as $N_\nu \leq 3$, whereas the accurate limit was $N_\nu \leq 3.94$.

[5]D. N. Schramm and R. V. Wagoner, Annu. Rev. Nucl. Sci. 27, 37 1977.

[6]J. R. Gott, J. E. Gunn, D. N. Schramm, and B. M. Tinsley, Astrophys. J. 194, 543 1974.

[7]K. A. Olive, D. N. Schramm, G. Steigman, and R. V. Wagoner, to be published.

[8]R. V. Wagoner, and G. Steigman, Phys. Rev. D, (to be published).

[9]S. L. Glashow, Sci. Am. 233, No. 4, 38 (1975).

[10]S. Weinberg, Trans. N. Y. Acad. Sci. 38, 185 (1977).

[11]K. A. Olive, D. N. Schramm, and G. Steigman, to be published.

CP Noninvariance in the Decays of Heavy Charged Quark Systems

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Within the context of a six-quark model combined with quantum chromodynamics we study the asymmetry in the decay of heavy charged mesons into a definite final state as compared with the charge-conjugated mode. We find that, in decays of mesons involving the b quark, measurable asymmetries may arise. This would present the first evidence for *CP* noninvariance in charged systems.

To date, the observation of *CP* nonconservation[1] has been limited to electrically neutral mesons. Effects in such systems are dominated by particle-antiparticle mixing in their mass and width matrices.[2] A striking prediction of *CP* nonconservation is that the decay rate of a particle into a definite final state can differ from the rate of the antiparticle decaying into the corresponding charge-conjugated state, namely[3] $\Gamma(i\to f) \neq \Gamma(\bar{i}\to\bar{f})$; of course, the *TCP* theorem guarantees that the total widths are identical.

In this paper, we present, in the context of definite models of *CP* nonconservation and the strong interactions, calculations for such asymmetries involving the decays of heavy charged mesons. We find, that although small, such an effect can be experimentally accessible, yielding the first evidence for time-reversal violation involving nonneutral systems.

Theoretically such an asymmetry does not occur at a tree-diagram level. It requires the presence of an absorptive part due to a loop integration. We will study processes where a combination of weak interactions and quantum chromodynamics (QCD) yield these necessary absorptive parts. We assume that the basic CP nonconservation is described by the Kobayashi and Maskawa[4] (KM) extension of the $SU(2) \otimes U(1)$ model of Weinberg and Salam.[5] The particle content of this model consists of three doublets of quarks and it incorporates a generalized Glashow-Iliopoulos-Maiani[6] mechanism. In addition to three Cabibbo-type angles, θ_1, θ_2, θ_3 the model can accommodate a CP-nonconserving phase δ.

We shall examine decays of mesons containing the b quark. There are two pairs of charged mesons: $B_u^- = (b, \bar{u})$, $B_u^+ = (\bar{b}, u)$; $B_c^- = (b, \bar{c})$, $B_c^+ = (\bar{b}, c)$. Collectively, we shall call these $B^\pm$. The asymmetries we have in mind are in the partial widths of $B_u^\pm \to \pi^\pm \pi^0$, $B_u^\pm \to K^\pm \pi^0$, etc., or in inclusive decays such as $B^+ \to \pi^\pm + X$ vs $B^- \to \pi^\mp + X$. These decays are dominated by diagrams in which the u or c quark is a spectator.[7] It is thus reasonable to study this CP- or T-nonconserving asymmetry at the quark level, namely in the decays of the "free" b quark.

The reaction of interest is

$$b \to f + q + \bar{q}, \tag{1}$$

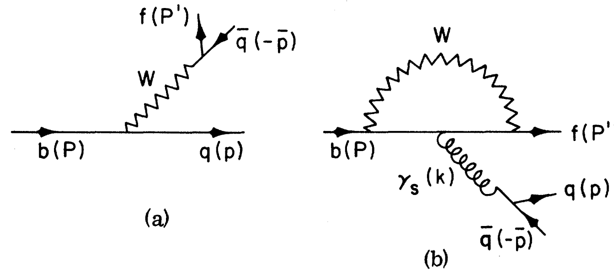

FIG. 1. Diagrams for the reaction $b(P) \to f(P') + q(p) + \bar{q}(-\bar{p})$, where $f = d$ or s. (a) The usual charged-current process, (b) contribution to the same reaction via gluon emission. (b) is the source for the absorptive part necessary for CP asymmetry. Note that gluon momentum is timelike unlike the case in "penguin diagrams" of Refs. 8 and 9.

with f (d or s), q, and $\bar{q}$ denoting quark flavors. If the charge of q is $\frac{2}{3}$ then the process can proceed via the first-order charged-current reaction of Fig. 1(a). To order $G_F \alpha_s$ (α_s is the QCD fine-structure constant) an absorptive part is obtained from the diagram of Fig. 1(b) which is like the "Penguin diagrams"[8-10] except that now $k^2 \geqslant 0$ (and *not* $\leqslant 0$). If the charge of q is $-\frac{1}{3}$, then Fig. 1(b) is the only diagram which contributes to (1). A nonvanishing absorptive part occurs whenever the quark line in the loop can be put on its mass shell; for b decay, intermediate c and u quark will satisfy this requirement. In the limit $m_w^2 \gg m_b^2$, Fig. 1(b) can be expressed as an effective weak Hamiltonian:

$$H_{bfq\bar{q}} \approx \sqrt{2}\, G_F (\alpha_s/\pi)(\textstyle\sum_j d_j I_j)(\bar{u}_f \gamma_{\mu L} \frac{1}{2} \lambda^\alpha u_b)(\bar{u}_q \gamma^\mu \frac{1}{2} \lambda^\alpha v_q), \tag{2}$$

where $\gamma_{\mu L} = \gamma_\mu (1 - \gamma_5)$, λ's are the color matrices (color indices are suppressed), and the sum extends over the intermediate states ($j = u, c, t$). The d_j's are angular factors extracted from the KM model[4] and I_j arises from the loop integral

$$I_j = \int_0^1 dx\, x(1-x) \ln[m_j^2/k^2 - x(1-x)]. \tag{3}$$

For $k^2 > 4m_j^2$ we obtain the desired absorptive parts leading to a difference in the widths for $b \to fq\bar{q}$ and $\bar{b} \to \bar{f} q \bar{q}$. As a measure of this difference we introduce the asymmetry parameter

$$a = (\Gamma_{bfq\bar{q}} - \Gamma_{\bar{b}\bar{f}q\bar{q}})/(\Gamma_{bfq\bar{q}} + \Gamma_{\bar{b}\bar{f}q\bar{q}}). \tag{4}$$

To indicate how frequently these decay modes occur we have also computed the ratio

$$r = \tfrac{1}{2}(\Gamma_{bfq\bar{q}} + \Gamma_{\bar{b}\bar{f}q\bar{q}})/\Gamma_b. \tag{5}$$

As long as s_2 is not approximately equal to $-s_3$, b decay will be dominated by the charged-current modes [via Fig. 1(a)], $b \to c\bar{u}d$ and $b \to c\bar{c}s$, and the sum of these rates defines Γ_b. If $s_2 = -s_3$, then these processes become suppressed, and many channels including the ones presented in connection with the asymmetry become important. We restrict our computations of r for values of s_2 and s_3 outside this region.

For numerical computations we used $\alpha_s = 0.35$, $\sin\theta_1 = 0.23$, $m_t = 15$ GeV, $m_b = 5$ GeV, $m_c = 1.5$ GeV, $m_s = 0.5$ GeV, and $m_u = m_d = 0.3$ GeV, and investigated the asymmetry for a range of values of θ_2 and θ_3. The value of the asymmetry was fairly insensitive to θ_3 but depended crucially on θ_2/θ_3.[11]

We divide the decay modes of the b into two groups. The first consists of those to which both

Figs. 1(a) and 1(b) contribute:

$$b \to du\bar{u}, \tag{6a}$$

$$b \to dc\bar{c}, \tag{6b}$$

$$b \to su\bar{u}, \tag{6c}$$

$$b \to sc\bar{c}. \tag{6d}$$

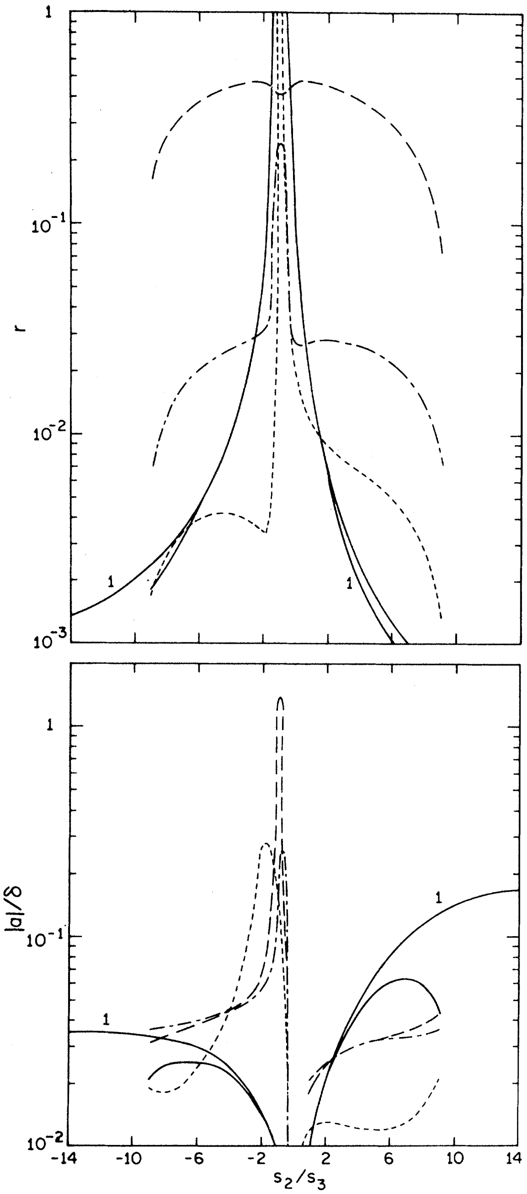

FIG. 2. The asymmetry parameter $|a|$ in units of δ and the ratio r defined in Eqs. (4) and (5), respectively, for Reactions (6a)–(6d). Solid curves for $b \to du\bar{u}$, dash-dotted line for $b \to dc\bar{c}$, short-dashed line for $b \to su\bar{u}$, and long-dashed line for $b \to sc\bar{c}$; $s_3 = 0.1$ except for label 1, where $s_3 = 0.02$. Results hold for small δ only (see Ref. 11).

In Fig. 2 we present the results for $|a|/\delta$ and r for the above reactions. These numbers are valid for a small value of δ. Most of the results are given for $s_3 = 0.1$, while for Reaction 6(a) we also present the values for $s_3 = 0.02$. For reactions with a strange quark in the final state, 6(c) and 6(d), the asymmetry can be a reasonable fraction of the total rate.

In Fig. 3 we show the results for decays involv-

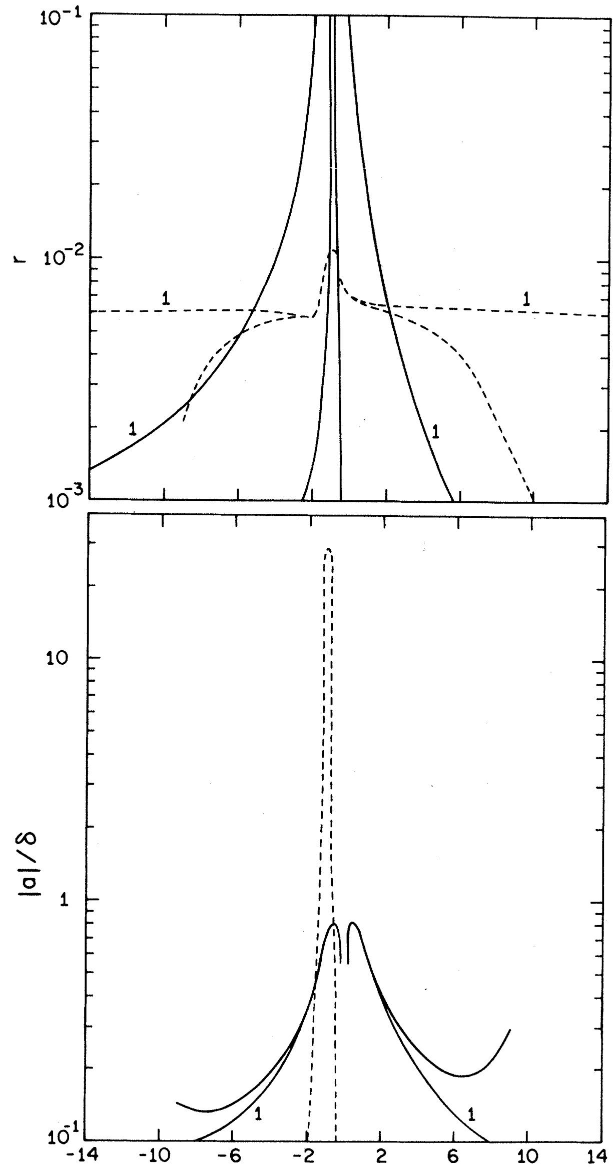

FIG. 3. $|a|/\delta$ and r for Reactions 7(a) and 7(b). Solid curves for $b \to dd\bar{d}$ and dashed ones for $b \to ss\bar{s}$. See caption for Fig. 2.

ing only Fig. 1(b), e.g.,

$$b \to d d \bar{d}, \tag{7a}$$

$$b \to s s \bar{s}. \tag{7b}$$

We note that a and r can be quite sizable and that an asymmetry in, say, $B^- \to K^-\eta$ (φ) vs $B^+ \to K^+\eta$ (φ) may range 20% for $\delta \approx \frac{1}{10}$. The rates for these channels may also be appreciable. In addition, should the timelike penguin diagrams [Fig. 1(b)] exhibit an enhancement similar to the one suggested for the spacelike momenta[8] then the asymmetries for Reactions (6) would also be enhanced as Fig. 1(b) would tend to dominate Fig. 1(a).[12]

Besides exclusive channels, inclusive ones should also reflect such asymmetries. If the charmonium history repeats itself and above the $B_u\bar{B}_u$ threshold there are resonances which decay predominantly into $B_u\bar{B}_u$ states, a way of detecting such effects may be to sit on one of these resonances and search for a difference in, say, the inclusive K^+ and K^- rates.

We would like to add a few remarks in brief:

(1) In Fig. 1(b) the gluon can be replaced by a photon so that our results for the asymmetry [Fig. 3(a)] for Reactions (7) also apply to effective weak neutral-current decays of the form $b \to d\ (s) + l^+ + l^-$. The corresponding value of r for these modes is smaller by a factor of $2\alpha^2/3\alpha_s^2$ compared to r of Fig. 3 for (7).

(2) We have also looked for similar effects in decays of s, c, and t quarks. For s and c quarks, and if m_t is much larger than m_b also for t quarks, the KM matrix leads to very small asymmetries (a). If charged mesons containing c quarks exhibit large CP nonconservation experimentally, then the KM model will be ruled out.

(3) The same mechanism also contributes to CP nonconservation in neutral mesons. However, we expect the effects from mass and width (zeroth order in α_s, in general) mixing to dominate in those systems.

(4) In the KM model the K-decay CP asymmetry parameter, $\epsilon \sim 2\times10^{-3}$, is proportional to $\sim s_2 s_3 \delta$.[9] Thus, in principle, δ could be quite large and the CP effects under discussion may be experimentally accessible with relative ease.

In conclusion we wish to emphasize that in this work we have exhibited how QCD enables us to calculate the CP asymmetries in decays of charged particles. As an illustration we have used the KM model. The same (and/or similar) mechanism(s) would lead to calculable effects in conjunction with any gauge model of CP nonconservation. In other models the resulting asymmetries, in general, would be quite different and may indeed be much larger for some reactions. Thus this mechanism may be used to constrain gauge models of CP nonconservation.

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[1] J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, Phys. Rev. Lett. 13, 138 (1964). For a recent review of this subject, see R. N. Mohapatra, in *Proceedings of the Nineteenth International Conference on High Energy Physics, Tokyo, 1978*, edited by S. Homma, M. Kawaguchi, and M. Miyazawa (Physical Society of Japan, Tokyo, 1979).

[2] L. Wolfenstein, Phys. Rev. Lett. 13, 562 (1966).

[3] Asymmetry in $K_L \to \pi^+ e^- \bar{\nu}$ vs $K_L \to \pi^- e^+ \nu$ results from the fact that K_L does not have any simple CP properties which can be attributed to the mass matrix.

[4] M. Kobayashi and T. Maskawa, Prog. Theor. Phys. 49, 652 (1973).

[5] S. Weinberg, Phys. Rev. Lett. 19, 1264 (1967); A. Salam, in *Proceedings of the Eighth Nobel Symposium on Elementary Particle Theory Relativisitc Groups, and Analyticity, Stockholm, Sweden, 1968*, edited by N. Svartholm (Almqvist and Wiksells, Stockholm, 1968), p. 367.

[6] S. L. Glashow, J. Iliopoulous, and L. Maiani, Phys. Rev. D 2, 1285 (1970).

[7] The simple t-channel exchange of a W between the b and $\bar{u}$ (or $\bar{c}$) quark does not exist for this situation. The s-channel $b\bar{u}$ annihilation involves at least two powers of sines of Cabibbo angles, is proportional to $\langle 0|J_{\text{weak}}|B\rangle$, and if the final state consists of light quarks is further suppressed by helicity arguments; the rate for the decay into a final state consisting of c and s quarks has a helicity suppression factor of $(m_c/m_b)^2 \sim \frac{1}{9}$. A gluon t-channel exchange (as opposed to the s-channel exchange considered subsequently in this Letter) may in some situations ($s_2 \approx -s_3$) be comparable to the terms which we study, but is unlikely to dominate them. (See M. K. Gaillard, in *Proceedings of the Summer Institute on Particle Physics, Stanford Linear Accelerator Center, July, 1978*, editor Martha C. Zipf, Stanford Univ. Press, California, 1978). Similarly, for the case of B_c system the spectator graphs are likely to be more important than the s-channel annihilation.

[8] M. A. Shifman, A. I. Vainshtein, and V. J. Zakharov, Nucl. Phys. B120, 316 (1977).

[9] Gaillard, Ref. 7.

[10] A previous application to CP noninvariance, of the penguin diagrams of Refs. 8 and 9, has been made by F. J. Gilman and M. B. Wise, SLAC Report No. SLAC-PUB-2243, 1978 (unpublished).

[11] Answers were insensitive to q^2 variations of α_s, and the value of m_t.

[12] The effective Hamiltonian (2) for Fig. 1(b) has the same $(V-A)V$ structure that is responsible for the $\Delta I = \frac{1}{2}$ enhancement proposed in Ref. 8 for the case of spacelike k^2.