CP Nonconservation in Decays of W and Z Bosons

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The possibility of CP asymmetries in decays of W and Z bosons is examined. The asymmetries studied are the differences in the branching ratios of charge-conjugate modes such as $W^+ \to t\bar{b}$ vs $W^- \to \bar{t}b$ or $Z \to \bar{b}s$ vs $Z \to b\bar{s}$. In the standard model, with three generations, such effects are found to be vanishingly small. With four generations, flavor-changing transitions such as $Z \to b\bar{s}$ or $b'\bar{b}$ may be observable, but the prospects for observing CP asymmetries appear discouraging. We also discuss the situation in some other models of CP nonconservation.

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One outstanding problem in particle physics is that the origin of the observed CP nonconservation[1,2] in the neutral-kaon system is not properly understood. It may be that the standard model (SM) with three generations is the underlying cause of CP nonconservation. However, the known facts on CP nonconservation are quite compatible even with Wolfenstein's phenomenological model[3] of CP which was proposed very shortly after the experimental discovery, i.e., way before the advent of gauge theories for electroweak interactions. The extreme paucity of experimental knowledge on CP has made it very difficult to distinguish between various theoretical alternatives. An important challenge therefore is to search for other arenas where CP nonconservation may make its presence felt. Motivated by these considerations we present here a study of CP asymmetry in the decays of W and Z bosons.[4] These bosons are important new thresholds in physics and study of their decays is one way of examining physics at a distance scale unaccessible heretofore. In the standard model with three generations we find that the resultant asymmetries are vanishingly small. However, to the extent that there is a lack of understanding of the origin of CP nonconservation, experimental searches for the effects may be worthwhile.

The asymmetries under consideration are (at the quark level) in two-body decays, e.g., $W^+ \to t\bar{b}$, $c\bar{b}$, etc., or $Z \to t\bar{c}$, $b\bar{s}$, etc. CP conservation requires that the partial widths of charge-conjugate modes be identical. Thus one can construct an asymmetry parameter, e.g.,

$$a_W = \frac{\Gamma(W^+ \to i\bar{f}) - \Gamma(W^- \to \bar{i}f)}{\Gamma(W^+ \to i\bar{f}) + \Gamma(W^- \to \bar{i}f)}. \qquad (1)$$

The underlying mechanism that contributes to such an asymmetry is very similar to the one proposed in the literature for B mesons.[5] A necessary criterion for a nonvanishing value for $a_{W/Z}$ is that the amplitudes for the relevant decays have an absorptive part. That in turn requires calculation of the amplitude to at least one-loop order with the possibility that the kinematics of the situation allow some of the intermediate particles to go on their mass shell. For the case of W decays (in the SM) it is easy to see that although the corrections to the Wtb vertex by emission and absorption of an arbitrary number of gluons (or photons or Z's) can generate an imaginary part, that is not sufficient to yield a nonvanishing contribution to a_W. Correction of the Wtb vertex by a single W emission and reabsorption is not possible so long as there are only charge $\frac{2}{3}$ and $-\frac{1}{3}$ quarks as is the case in the SM. Thus a nonvanishing contribution to a_W can arise only via two-loop (i.e., with two W exchanges) corrections to the tree graph and consequently is expected to be extraordinarily small.

For Z decays into two-body modes with mixed quark flavors (such as $Z \to t\bar{c}$, $b\bar{s}$, etc.) a nonvanishing contribution to a_Z can arise through the W-exchange graph as shown in Fig. 1. Furthermore, since there is no tree-graph contribution to these decays the real and imaginary parts both arise at the same order in the gauge coupling. So, in principle, CP asymmetries in such decays can be much larger than in those processes in which the asymmetry arises through interference of tree and loop graphs. But the problem is that in the SM with three generations the rates for these modes have been estimated to be vanishingly small: Using the works[6] of Clements *et al.* and

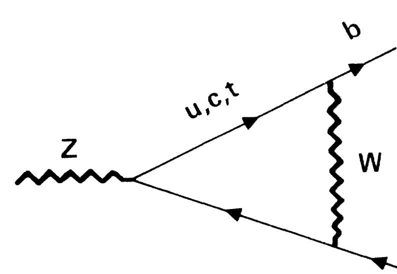

FIG. 1. A diagram contributing to flavor-changing Z decay (e.g., $Z \to b\bar{s}$) in the three-generation case.

Ganapathi *et al.* and substituting the values of the relevant Kobayashi-Maskawa (KM)[7] parameters that have become known (e.g., $V_{cb} \cong 0.04$ and $V_{ts} \cong 0.04$) we estimate that the branching ratio for $Z \rightarrow b\bar{s} + \bar{b}s$ is about 10^{-9} to 10^{-8} for $m_t = 40$ to 100 GeV. The branching ratio for $t\bar{c}$ final states is even smaller. The rates for the modes are so small that the question of whether the *CP* asymmetry is small or large is purely academic. In any case, through unitarity of the KM matrix and our present knowledge about its elements, one can easily see that the expected *CP* asymmetry itself is very small in the three-generation case. In the context of the standard model the only possibility of observation is then if there are more than three generations.

For the case of four generations one cannot make estimates with a great degree of reliability as the masses and mixing angles are largely open to speculation. By now there are many parametrizations for the 4×4 mixing matrix that are available in the literature. Among those we will use the following as illustrative examples: Cheng and Li,[8] Pakvasa[9] (a), Pakvasa[9] (b), and Botella and Chau.[10]

Cheng and Li (CL) extend Wolfenstein's[11] parametrization of the KM matrix. This extension is built on rather strong theoretical prejudice, i.e., an anticipation of a repetition of the Fritzsch[12] hierarchy for the fourth generation and the assumption that m_u is anomalously low. It suggests $m_{b'} \cong 60$ GeV and $m_{t'} \cong 450$ GeV. Pakvasa's parametrizations[9] are based on the assumption that V_{ub} is severely suppressed. Botella and Chau (BC)[10] are more phenomenological and take the 2×2 submatrix that is important for the discussion at hand as

$$\begin{pmatrix} V_{tb} & V_{tb'} \\ V_{t'b} & V_{t'b'} \end{pmatrix} = \begin{pmatrix} C_u & S_u \\ S_u & C_u \end{pmatrix}. \qquad (2)$$

The contribution of the jth quark flavor in the loop to a given final state (say $f_1\bar{f}_2$) can be estimated to be proportional to $V_{jf_1} V_{jf_2}^* m_j^2$. Thus, for example, the contribution of the t loop to $b\bar{s}$ is proportional to m_t^2, etc. In this way one can easily estimate the rates for various final states. The results for the branching ratio (B) and the expected *CP* asymmetry (a_Z) for the four models mentioned above are given in Table I for two of the most promising final states: $b\bar{s}$ and $b'\bar{b}$.

From Table I we see that the CL model appears to be highly pessimistic for both modes. Recalling that the upcoming Z factories such as the Stanford Linear Collider and the CERN e^+e^- collider LEP may produce about 10^6 Z's per year, we see that both the $b\bar{s}$ and $b'\bar{b}$ modes may have observable branching ratios in the models of Pakvasa and Bottella and Chau. The $b\bar{s}$ could have $B \sim 10^{-6}$ whereas $b'\bar{b}$ could be as much as 10^{-4}–10^{-5}. We also note in passing that experimentally the identification of the $b\bar{s}$ mode may be much more problematic than the $b'\bar{b}$ mode. We also see from Table I that the minimum number (indicated by $N \geqslant 1/Ba_Z^2$) of Z decays required to see *CP* asymmetry in these modes appears to be more than 10^8. So, while the flavor-nondiagonal Z decays may be observable, it seems that at least in the SM the possibility of observing *CP* nonconservation is remote.

It is of interest to get a qualitative understanding of Table I. A prerequisite for observing an asymmetry in rates is to have substantial partial rates, which can be achieved by demanding a heavy fourth-generation quark in the loop. However, for a broad range of quark masses, the situation regarding the observability of *CP* asymmetry does not improve. For while we increase the heavy-quark mass (m_Q), the absorptive part of the amplitude is constrained by the condition that the internal quark mass has to be less than $m_Z/2$. Thus, when other parameters are held fixed, B tends to increase as m_Q^4 whereas a_Z tends to decrease as m_Q^{-2}. So for a broad range of values of m_Q, the situation for the observability of *CP*, being controlled by $\sim (Ba_Z^2)^{-1}$, remains unaffected.

TABLE I. Summary of branching ratio (B), *CP* asymmetry (a_Z), and minimum number ($N = 1/Ba_Z^2$) required for observability of *CP* asymmetry. ϕ is a typical *CP*-nonconserving phase and C_u, S_u are defined in Eq. (2). The inequality signs imply that the numbers are obtained by maximation of the possible asymmetry. We have assumed that $m_t < M_Z/2$ and have used $M_{t'} \approx 500$ GeV and $m_{b'} \sim 60$ GeV in the numerical estimate. For Botella and Chau, ranges indicated depend on the choice of their parameters.

Mode	Quantity	Cheng and Li	Pakvasa (a)	Pakvasa (b)	Botella and Chau
$Z \rightarrow b\bar{s} + \bar{b}s$	B	3×10^{-10}	5×10^{-6}	10^{-6}	10^{-8} to 2×10^{-6}
	a_Z	$\leqslant 80\%$	$< 1\%$	$\leqslant 1\%$	< 7 to $< 80\%$
	N	$> 5 \times 10^9$	$> 2 \times 10^9$	$> 10^{10}$	$> 10^8$
$Z \rightarrow b'\bar{b} + \bar{b}'b$	B	$(1$ to $9) \times 10^{-7}$	10^{-5}	10^{-5}	$(5$ to $40) \times 10^{-5} C_u^2 S_u^2$
	a_Z	$< 10^{-4} \sin\phi$	0.1%	0.2%	$2 \times 10^{-4} \sin\phi / C_u S_u$
	N	$>> 10^{12}$	$> 10^{11}$	$> 2 \times 10^{10}$	$\geqslant 10^{11}$

Let us next note, very briefly, that the expected B for the $t\bar{c}$ mode (in the SM with four generations) is still much smaller than the $b\bar{s}$ mode. Of course, once again, that ought to encourage experimentalists to search for the $t\bar{c}$ mode as its observation would signal departure from the SM.

We now briefly discuss the situation in some extensions of the standard model. We first consider the possibility of a real KM matrix with CP nonconservation arising from horizontal gauge interactions. For definiteness, we restrict our consideration to one such model[13] which is based on $SU(2)_L \otimes SU_R(2) \otimes U(1)$ with right-handed components of the three families in an adjoint representation of $SU_R(2)$ which is the horizontal gauge group. The model has one dominant phase as $c \leftrightarrow t$ or $s \leftrightarrow b$ transition with horizontal-gauge-boson emission. The K_L-K_S mass difference then restricts the mass of the horizontal gauge boson to be ≥ 5 TeV whereas the observed CP nonconservation requires that the mass ≤ 60 TeV.[13]

The model does not give rise to flavor-changing quark-antiquark decays of Z bosons as horizontal-gauge-boson exchange conserves horizontal charge. Thus, e.g., a virtual $c\bar{c}$ pair with horizontal charge 0 cannot change to $t\bar{c}$ (which has a nonvanishing horizontal charge) by emitting horizontal gauge bosons. A loop correction to the tree-graph amplitude for W-boson decays does exist as shown in Fig. 2. Thus a nonvanishing value for a_W can arise in the model. However, on interference with the tree graph (which is purely left handed) the amplitude becomes proportional to internal and external quark masses. For the $t\bar{b}$ mode, the asymmetry, consequently, has the following structure (ϕ is the CP-nonconserving phase)[13]:

$$a_W = (g_R^2 \sin\phi / M_{\mathcal{R}}^2)\, m_t m_c m_s m_b / M_W^2, \tag{3}$$

which is $\sim 10^{-12}$! Now the dependence of this expression on quark masses is a direct result of our choice of putting the right-handed components of fermions into representations of the horizontal group. This choice has some theoretical advantages but could hardly be guaranteed. Therefore we have examined the consequences of a left-handed horizontal interaction as well.[14] The generic structure of the asymmetry then has the form

$$a_W = (5/24\pi) f(V_{\rm KM}) (g_R^2 \sin\phi / \overline{M}_{\mathcal{R}}^2) M_W^2 = 10^{-4} f(V_{\rm KM}) \tag{4}$$

and $f(V_{\rm KM})$ is a function of $V_{\rm KM}$, where $\overline{M}_{\mathcal{R}}^2$ is some "phase-space reduced" effective $M_{\mathcal{R}}^2$. Again a_W is discouragingly small even if one uses the most optimal bound for $M_{\mathcal{R}}$, i.e., ≥ 2 TeV.

The left-right-symmetric model has the W_R mass limit $M_R \geq 2$ TeV.[15] Thus we do not expect any sizable a_Z and the situation for a_W is the same as in the SM.

Another model of interest is the Weinberg model of CP nonconservation.[16] The model has three Higgs doublets, with natural flavor conservation and spontaneous CP nonconservation, which has a consequence[17] that the KM matrix V is real and CP nonconservation occurs through Higgs exchange. It has been argued[18] that this model gives rise to too large a value for ϵ'/ϵ. However, recently Branco, Buras, and Gerard[19] (BBG) have resuscitated the model. They find that if an interesting hierarchy[20] among the vacuum expectation values of the Higgs doublets is satisfied, the model can accommodate all known experimental constraints, including ϵ'/ϵ and neutron electric dipole moment.

In the Weinberg model, loop corrections to Z decay via charged Higgs exchange are very similar to the unphysical scalar exchange graphs in the standard model, except that now there are more parameters. One has the usual charged (unphysical) Higgs-Yukawa couplings modulated by ratios of mixing matrix elements in the charged-Higgs-boson sector (which arises analogously to the KM matrix when the Higgs-boson mass matrix is diagonalized), and also the two physical Higgs-boson masses enter in the boson exchange propagator, in place of M_W. Although in the standard model, as stated earlier, one finds a negligibly small result for $B(Z \to b\bar{s} + \bar{b}s) \sim 10^{-9}$, the reason for it to be nonvanishing at all is due to insufficient Glashow-Iliopoulos-Maiani cancellation because of unequal quark masses that enter into the coupling of longitudinal W bosons (i.e., unphysical scalar Yukawa couplings) to quarks. In the Weinberg type of models, Glashow-Iliopoulos-Maiani cancellation is expected to be far less effective since there are additional parameters. For instance, in the analysis of BBG,[19] if one makes one of the physical Higgs bosons very heavy,[21] it is found that the intrinsic CP-nonconserving phase is about 0.02, whereas various *amplitudes* in Z decay via Higgs-boson exchange may gain enhancement factors up to 2×10^2–2×10^4. Thus, one cannot rule out the possibility that in the Weinberg model one may have large flavor-changing Z decay rates together with ob-

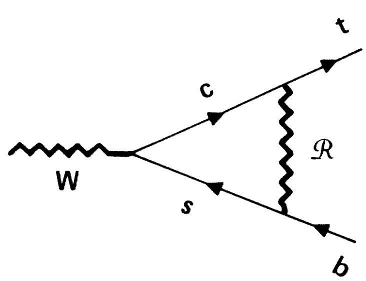

FIG. 2. A possible loop correction to the usual tree graph for, say, $W \to t\bar{b}$. $\mathcal{R}$ is a horizontal gauge boson.

servable CP nonconservation. Note that in the analogous, but not identical, situation of the neutron electric dipole moment (the graphs are similar, with γ replacing Z; the difference is that in Z decay we rely on absorptive parts of the amplitude to exhibit CP nonconservation), it is the Weinberg model, among all popular models, that gives the largest value. Hence, it is possible that in the case of Z decay, if the parameters of the Weinberg model are favorable it may lead to interesting CP-nonconserving asymmetries.[22]

We note in passing the situation concerning supersymmetric extensions of the SM. The gluon contribution to $Z \rightarrow t\bar{c}$ has been considered and the possible B are not encouraging.[23] The W-ino contribution is expected to be smaller because the gauge coupling is weak. However, the Higgs fermion couples to squark–quark analogous to the usual Yukawa couplings and here again, as in the Weinberg type of models,[16,19] there may be interesting effects.[22,24]

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Note added.—After submission of this paper we learned of the related work of Bernabeu, Gavela, and Santamaria.[25] We consider more cases in the SM with four generations as well as some extensions of the SM and we particularly emphasize the $\bar{b}b'$ mode. It may be useful to clarify the difference between the two works on the $b\bar{s}$ mode where Bernabau, Gavela, and Santamaria appear more optimistic than us. This is, in part, because they have taken $V_{t's} \sim \theta_C = 0.22$, which we feel is rather unrealistically optimistic, and we take $V_{t's} \sim \theta_C^2$.

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[1]J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turley, Phys. Rev. Lett. **13**, 138 (1964).

[2]For recent reviews see L. Wolfenstein, Carnegie-Mellon University Report No. CMU-HEP-86-3, 1986 (to be published); L.-L. Chau, invited talk at the Meson 50 Conference, Kyoto, 15–17 August 1985 (to be published); A. J. Buras, in *Proceedings of the International Europhysics Conference on High-Energy Physics, Bari, 1985* (European Physical Society, Geneva, 1985); J. D. Bjorken, in *Proceedings of the Twentieth Rencontre de Moriond, 1985,* edited by J. Tran Thanh Van (Editions Frontieres, Gif-sur-Yvette, France, 1985).

[3]L. Wolfenstein, Phys. Rev. Lett. **13**, 562 (1964).

[4]Preliminary results of this work were presented by A. Soni, in Proceedings of the Workshop on Standard Model Physics at the Superconducting Super Collider, Los Angeles, California, 1986, edited by H.-U. Bengtsson, C. Buchanan, T. Gottschalk, and A. Soni (to be published).

[5]M. Bander, D. Silverman, and A. Soni, Phys. Rev. Lett. **43**, 242 (1979). See also N. G. Deshpande, G. Eilam, A. Soni, and G. L. Kane, Phys. Rev. Lett. **57**, 1106 (1986).

[6]M. Clements, C. Footman, A. Kronfeld, S. Narasimhan, and D. Photiadis, Phys. Rev. D **27**, 570 (1983); V. Ganapathi, T. Weiler, E. Laermann, I. Schmitt, and P. M. Zerwas, Phys. Rev. D **27**, 879 (1983). See also G. Eilam, Phys. Rev. D **26**, 1202 (1983); A. Axelrod, Nucl. Phys. **B209**, 349 (1982); K. I. Hikasa, Phys. Lett. **148B**, 221 (1984).

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

[8]T. P. Cheng and L.-F. Li, Phys. Rev. Lett. **55**, 2249 (1985).

[9]S. Pakvasa, National Laboratory for High Energy Physics-KEK Report No. TH-112-(1985) (to be published); X-G. He and S. Pakvasa, Phys. Lett. **156B**, 236 (1986). Reference to other works on fourth generation may be found in these papers.

[10]F. J. Botella and L. L. Chau, Phys. Lett. **168B**, 97 (1985).

[11]L. Wolfenstein, Phys. Rev. Lett. **51**, 1945 (1977).

[12]H. Fritzsch, Phys. Lett. **70B**, 436 (1977).

[13]W.-S. Hou and A. Soni, Phys. Rev. Lett. **54**, 2083 (1985).

[14]Left-handed horizontal interactions are motivated by work that is in progress by one of us (A.S.) with Jeff Carpenter and Richard Norton.

[15]G. Beall, M. Bander, and A. Soni, Phys. Rev. Lett. **49**, 848 (1982).

[16]S. Weinberg, Phys. Rev. Lett. **37**, 657 (1976).

[17]G. C. Branco, Phys. Rev. Lett. **44**, 504 (1980).

[18]A. I. Sanda, Phys. Rev. D **23**, 2647 (1981); N. G. Deshpande, Phys. Rev. D **23**, 2654 (1981); J. F. Donoghue, J. S. Hagelin, and B. R. Holstein, Phys. Rev. D **25**, 195 (1985).

[19]G. C. Branco, A. J. Buras, and J.-M. Gerard, Phys. Lett. **155B**, 192 (1985), and Nucl. Phys. **B259**, 306 (1985).

[20]See, however, Y. Dupont and T. N. Pham, Phys. Rev. D **29**, 2169 (1983); J. F. Donoghue and B. R. Holstein, Phys. Rev. D **32**, 1152 (1985). We note that these works imply that the BBG hierarchy may not be necessary for the Weinberg models.

[21]CP nonconservation would also vanish if the physical charged-Higgs-boson masses are degenerate.

[22]Work along these lines is in progress.

[23]M. J. Duncan, Phys. Rev. D **31**, 1139 (1985).

[24]We are grateful to Antonio Masiero, Balachandran Sathiapalan, and Herbert Steger for discussions.

[25]J. Bernabeu, M. B. Gavela, and A. Santamaria, CERN Report No. CERN-TH-4381/86 (unpublished).