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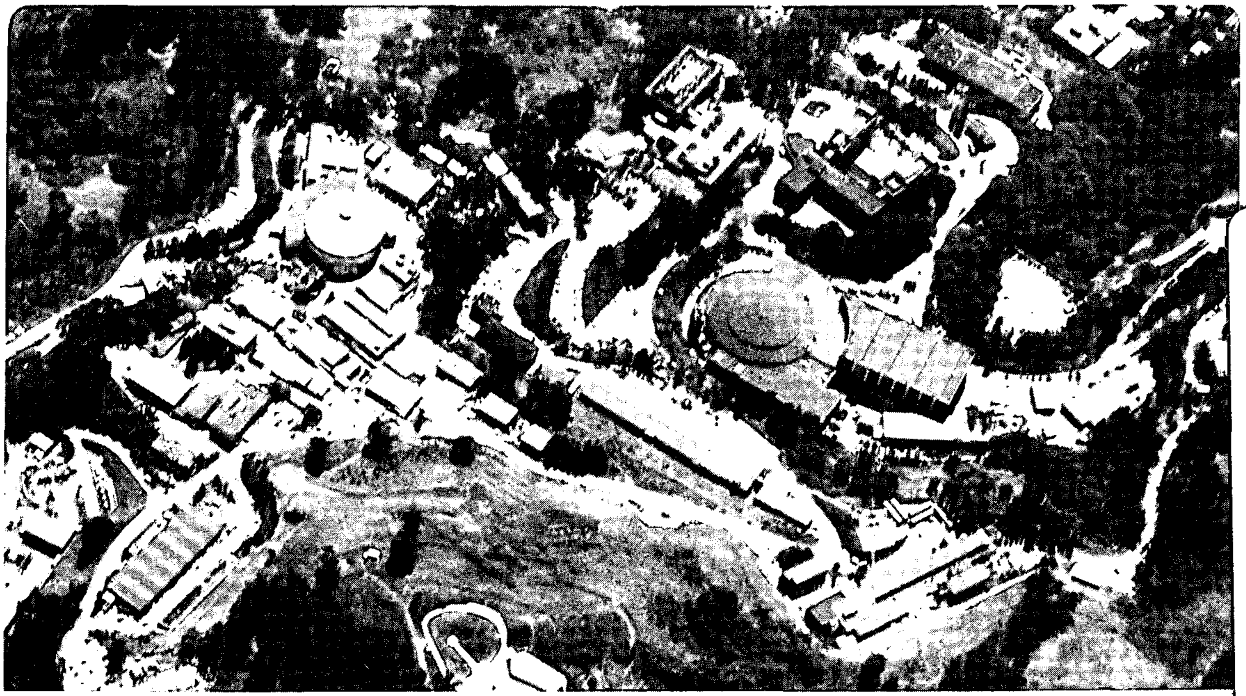

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CP Violation at the Z Peak. *

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Abstract

Some possibilities for searches of CP–nonconservation in decays of the Z boson produced in e^+e^- collisions are briefly reviewed.

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CP violation, which so far has been observed only in the neutral kaon system, arises in the 3 generation standard model (SM) from the charged weak quark current couplings and is parameterized by a CP–violating phase in the Kobayashi–Maskawa (KM) matrix. Since the origin of CP violation is not understood it is important to search for CP–nonconserving effects in physical situations other than the $K^0-\bar{K}^0$ system. The Z peak can be used for this purpose. However, if KM mixing in the quark sector is the only source of CP violation in Nature it is very unlikely that the luminosity of LEP suffices for observing CP–violating phenomena at the Z peak – e.g., by detecting CP–violating same–sign dilepton asymmetries or specific CP–violating non–leptonic decays of B mesons produced in $Z \to b\bar{b}$. Estimates indicate – see, for instance [1] – that an integrated luminosity of at least $10^{40} cm^{-2}$ would be needed to measure at the Z peak CP violation induced by the KM mechanism. That is, CP tests at LEP very probably are sensitive to possible new forces of CP violation only. Especially one may imagine CP–violating forces which become visible only at energies around the Z mass or higher. Other proposals made so far to search for CP nonconservation in Z decays may be classified as follows:

I) Rare events

a) CP–violating 2–body channels: Since the Z boson, being produced by the standard neutral current, is an eigenstate of CP [CP(Z) = +1] in its rest system, one may look (in analogy to $K_L^0 \to 2\pi$) for decays of the Z which would imply CP violation. CP–violating channels are $Z \to P_1P_2$, where $P_1, P_2 = \pi^0, \eta, \eta', K_L^0, \eta_c, \eta_b, ...$ are $J^{PC} = 0^{-+}$ states and $Z \to S_1S_2$ where $S_1, S_2 = \chi_{c0}, \chi_{b0}, ...$ are $J^{PC} = 0^{++}$ states. The particles P_1 and P_2 (respectively S_1 and S_2) have the same C and P but are in a p wave, i.e., in a P- and CP-odd state. (Note that $P_1 = P_2$ and $S_1 = S_2$ final states are forbidden by Bose symmetry.) Estimates of branching ratios of these channels within non–standard models of CP violation would be desirable.

b) CP–violating asymmetries in flavor–violating decays: The asymmetry

$$\alpha = \frac{\Gamma(Z \to s\bar{b}) - \Gamma(Z \to \bar{s}b)}{\Gamma(Z \to s\bar{b}) + \Gamma(Z \to \bar{s}b)} \tag{1}$$

and others involving $q'\bar{q}$ pairs such as $\bar{d}s, \bar{d}b$ (which are probably less favorable than the $\bar{s}b$ channel) were studied in Refs. [2,3]. Whereas in the 3 generation SM $B \cdot \alpha \lesssim 10^{-12} \sin\delta$ (B denotes the branching ratio for $Z \to s\bar{b}, \delta$ is the CP-violating KM phase), this product can be much larger in the 4 generation case: It has been estimated [2,3] that $B \simeq 10^{-7}$ to 10^{-6} and the asymmetry $\alpha \simeq$ to be of order .1. That is, in the most favorable case the minimum number of Z decays required to see the CP asymmetry (1) appears to be more than $N = (B\alpha^2)^{-1} = 10^8$. In the 4 generation case $B(Z \to b'\bar{b})$ could be larger [2] than $B(Z \to s\bar{b})$ and the $b'\bar{b}$ channel would also be less problematic to detect than $s\bar{b}$. However $\alpha_{b'\bar{b}}$ was estimated [2] be at least one order of magnitude smaller than $\alpha_{s\bar{b}}$. For a 2 Higgs–doublet model it was found recently [15] that $B(Z \to b\bar{s}) < 2 \cdot 10^{-6}$. Within the minimal supersymmetric (SUSY) extension of the SM $B(Z \to s\bar{b}) \simeq 2.4 \times 10^{-9}$ was obtained [16]. For non–minimal SUSY extensions this branching ratio was found to be at most one order of magnitude larger [17]. Other flavor–violating channels also have tiny branching rations [16, 17, 18]. That is, even if SUSY or Higgs models of CP violation may allow for large asymmetries (1) these models offer little hope that these asymmetries may be observed at LEP.

c) CP-odd correlation in $Z \to H^0\ell^+\ell^-$: Another "exotic" CP test which requires the production of much more than $10^6 Z$'s – if it is possible at all – was investigated in [5]. If the decay $Z \to H^0\ell^+\ell^-$, where H^0 is the Higgs particle, is kinematically possible (recall that $B(Z \to H^0\mu^+\mu^-) \leq 6 \cdot 10^{-5}$ if $m_H \geq 10$ GeV) and sufficient events are available, then one may check whether this decay is affected by a CP–violating interaction by measuring CP–odd correlations such as $\boldsymbol{\lambda} \cdot (\hat{\mathbf{k}}_+ \times \hat{\mathbf{k}}_-)$. Here $\boldsymbol{\lambda}$ is the vector polarization of the Z (see below) and $\hat{\mathbf{k}}_\pm$ are the momentum direction vectors of $\ell^\pm$.

II. *CP*–odd correlations in some main 2– and 3–body decay modes

Another possibility is to use some of the main Z decay modes, such as $Z \to \tau^+\tau^-, Z \to \ell^+\ell^-\gamma (\ell = e, \mu, \tau), Z \to 2$ jets $+\gamma, Z \to 3$ jets for CP tests. Appropriate observables are CP–odd correlations involving the momentum directions of the outgoing states (for $Z \to \tau^+\tau^-$ also τ polarization) and the polarizations of the Z boson. Some of the observables discussed below also require flavor tagging. A systematic study of how these decay modes can be used for CP tests was made in [6,7]; specific proposals were made in [8,9]. CP tests in e^+e^- collisions away from the Z resonance were considered in [10, 11, 12]. Before discussing CP–odd correlations let us recall that the spin density matrix of the Z boson being produced with unpolarized e^+e^- beams as with LEP, is

$$\rho_{ab} = \frac{1}{3}\delta_{ab} + \frac{1}{2i}\epsilon_{abc}\lambda_c - \lambda_{ab} \tag{2}$$

where, to lowest order perturbation theory, the vector (tensor) polarization $\lambda_a(\lambda_{ab})$ is [7]

$$\boldsymbol{\lambda} = .16\hat{\mathbf{p}}, \quad \lambda_{ab} = diag\left(-\frac{1}{6}, -\frac{1}{6}, \frac{1}{3}\right). \tag{3}$$

Here $\sin^2\theta_W = .23$ is used and the unit momentum vector $\hat{\mathbf{p}}_+$ of e^+ is chosen along the z axis.

a) $Z \rightarrow \tau^+\tau^-$: This mode can be used to search for CP–violating dipole form factors of the τ [9, 14]. In order to form CP–odd correlations in $Z \rightarrow$ fermion antifermion, one needs to know the polarization vectors of the outgoing fermions. Measurement of polarizations is feasible for $\tau^+\tau^-$ final states [13], most efficiently through $\tau \rightarrow \pi\nu_\tau$. (The standard $V-A$ interaction at the $\tau\nu_\tau$ vertex is assumed.) Let $\hat{\mathbf{s}}_\pm$ be the polarization vectors of $\tau^\pm$ in their respective rest–frames ($\hat{\mathbf{s}}_\pm^2 = 1$) and let $\hat{\mathbf{k}}$ be the CMS momentum direction vector of τ^+. Using the polarization tensors (4) of the Z, the following CP–odd (but CPT–even) correlations linear in $\mathbf{s} = \hat{\mathbf{s}}_+ - \hat{\mathbf{s}}_-$ can be formed:

$$(\hat{\mathbf{k}} \times \mathbf{s}) \cdot \boldsymbol{\lambda}, \quad \lambda_{ij}(\hat{k}_i n_j + \hat{k}_j n_i), \tag{4}$$

where $\mathbf{n} = \hat{\mathbf{k}} \times \mathbf{s}$. For measuring these correlations one must infer the momentum direction of the τ's. This will not be possible in general. A more useful correlation is

$$\boldsymbol{\lambda} \cdot (\hat{\mathbf{s}}_+ \times \hat{\mathbf{s}}_-). \tag{5}$$

It can be measured in $Z \rightarrow \tau^+\tau^- \rightarrow \pi^+\overline{\nu}_\tau\pi^-\nu_\tau$; i.e., one measures $\boldsymbol{\lambda} \cdot \mathbf{p}_{\pi^+} \times \mathbf{p}_{\pi^-}$. For an on–shell Z the correlations (4), (5) are proportional to a CP–violating weak dipole from factor $\tilde{d}_\tau(q^2 = M_Z^2)$ which is generated by the effective interaction

$$\mathcal{L}_{CP} = -(i/2)\tilde{d}_\tau\bar{\tau}\sigma^{\mu\nu}\gamma_5\tau(\partial_\mu Z_\nu - \partial_\nu Z_\mu). \tag{6}$$

For instance, one finds [14] that

$$\langle \boldsymbol{\sigma}_+ \times \boldsymbol{\sigma}_- \rangle = -\frac{4\hat{d}_\tau}{g_A}\boldsymbol{\lambda} \tag{7}$$

where $g_A = -1/2$ and the dimensionless form factor $\hat{d}_\tau$ is defined by $\tilde{d}_\tau = e(\sin\theta_W \cos\theta_W M_Z)^{-1}\hat{d}_\tau = 5.2 \times 10^{-16}\hat{d}_\tau$ [ecm]. By means of (7) $\tilde{d}_\tau \gtrsim 10^{-17}$ ecm could be detected assuming $10^6 Z$'s. In [9] it was suggested to search for an electric dipole form factor of the τ (generated by an effective interaction $-(i/2)d_\tau \bar{\tau}\sigma^{\mu\nu}\gamma_5 \tau F_{\mu\nu}$ by means of a CP–odd correlation analogous to (5). If one scans through the Z peak and selects events $e^+e^- \to \tau^+\tau^- \to \pi^+\bar{\nu}_\tau\pi^-\nu_\tau$ then one may search for the correlation $\hat{\mathbf{p}}_+ \cdot (\hat{\mathbf{k}}_+ \times \hat{\mathbf{k}}_-)$ where $\hat{\mathbf{k}}_\pm$ are the momentum directions of $\pi^\pm$. This correlation is, however, of order α compared to (7) in the vicinity of the Z peak. Moreover, $\langle \hat{\mathbf{p}}_+ \cdot (\hat{\mathbf{k}}_+ \times \hat{\mathbf{k}}_-)\rangle$ is suppressed by a factor $g_V = -.04$ and vanishes in Born approximation at the Z resonance (assuming d_τ to be real). Therefore the sensitivity is limited to $d_\tau \gtrsim 10^{-15}$ecm [9]. Obtaining these numbers for $\tilde{d}_\tau$ and d_τ would be a non–trivial accomplishment. "Large" values for $\tilde{d}_\tau$, d_τ are conceivable. For instance, in Weinberg–type models [4] of CP violation in the lepton sector d_{lepton}, $\tilde{d}_{lepton}$ can grow like m^3_{lepton}.

b) 3–body decays: Here, no polarization measurements are necessary to set up CP tests. In the radiative decays

$$Z \to \ell^+\ell^-\gamma,\ Z \to \bar{q}q\gamma \to 2 \text{ jets} + \gamma(\text{tagged jets})$$

the following CP–odd, CPT–even correlations can be searched for [6,7]:

$$\boldsymbol{\lambda} \cdot (\hat{\mathbf{k}}_+ \times \hat{\mathbf{k}}_-) \tag{8}$$

$$\lambda_{ij}[\hat{k}_{+i}\hat{n}_j - \hat{k}_{-i}\hat{n}_j + ((i \leftrightarrow j))] \quad . \tag{9}$$

where $\hat{\mathbf{n}} = (\mathbf{k}_+ \times \mathbf{k}_-)/\,|\mathbf{k}_+ \times \mathbf{k}_-|$ and $\hat{\mathbf{k}}_\pm$ are the unit momenta of $\ell^\pm$ (respectively $\bar{q}$ and q). One may also look for the correlation $\boldsymbol{\lambda}\cdot\hat{\mathbf{k}}_\gamma$[8,7] which is CP–and CPT–odd. That is, CP-violating and final state interactions are required to render this correlation non–zero.

One can avoid flavor tagging and define jets through a CP–blind ordering criterion [10]. (Of course, also the jet finding algorithm need not have a CP–bias.) For instance one may order the jets according to their "fastness", *i.e.*

$$|\mathbf{k}_{jet\ 1}| \geq |\mathbf{k}_{jet\ 2}| \geq \cdots . \tag{10}$$

Using such a criterion one can use the decays

$$\begin{aligned} Z &\rightarrow jet\ 1(\mathbf{k}_1) + jet\ 2(\mathbf{k}_2) + \gamma(\mathbf{k}_3) \\ Z &\rightarrow jet\ 1(\mathbf{k}_1) + jet\ 2(\mathbf{k}_2) + jet\ 3(\mathbf{k}_3) \end{aligned} \tag{11}$$

to search for CP–odd correlations [6,7]. The most useful ones are

$$\lambda_{ij}[\hat{k}_{ai}\hat{n}_j + (i \leftrightarrow j)],\ a = 1,2,3 \tag{12}$$

where $\hat{\mathbf{k}}_{1,2}$ are the unit momenta of the fastest and the second–fastest jet, respectively, and $\hat{\mathbf{n}} = (\mathbf{k}_1 \times \mathbf{k}_2)/|\mathbf{k}_1 \times \mathbf{k}_2|$. Note that charge conjugation leaves the momentum variables of the jets in (11) defined by (10) unchanged, whereas under P,T: $\mathbf{k}_a \rightarrow -\mathbf{k}_a$. That is, the correlations (12) are CP-odd, but CPT–even. The correlations $\hat{\mathbf{k}}_a \cdot \boldsymbol{\lambda}$ are CP–and CPT–odd. Hence they require apart from CP violation also final state interactions in order to be non–zero.

The correlations (8), (9), and (12) were calculated in [6,7], for various energy and angular cuts, in terms of the parameters of an effective Lagrangian, which contains CP–violating interactions up to and including dimension $d = 6$ operators. The correlations (9) and (12) are sensitive to chirality conserving $\bar{f}fZ\gamma$, respectively $\bar{q}qZ$ gluon interaction terms (f=fermion), whereas (8) is, for given f, also affected by a chirality–flipping dipole interaction given by (6) with $\tau \rightarrow f$. Its contribution to (8) suffers from a helicity suppression factor m_f/M_z. Therefore it is of possible relevance only when (8) is evaluated for heavy flavors.

Associating an energy scale Λ_{CP} with the new CP–violating forces which generate in particular the $d = 6$ operators, one finds that by measuring (9), (12) at LEP1 one is sensitive to $\Lambda_{CP} \lesssim 1$ TeV. Nontrivial information on CP-violating interactions involving the heavy flavors τ, c, b – at least upper bounds on CP–violating couplings – can be obtained in this way.

If KM mixing in the only cause of CP violation (7), (8), (9), and (12) are unobservably small. Among the various "nonstandard" models of CP violation considered in the literature Higgs–boson models probably describe the most sizeable potential source of CP violation in Z boson decays and in other high energetic reactions.

References

1. W.B. Atwood, I. Dunietz, and P. Grosse–Wiesmann, *Phys. Lett.* **B216**, 227 (1989); Erratum to be published.
2. W.S. Hou, N.G. Deshpande, G. Eilam, and A. Soni, *Phys. Rev. Lett.* **57**, 1406 (1986).
3. J. Bernabéu, A. Santamaria, and M. B. Gavela, *Phys. Rev. Lett.* **57**, 1514 (1986).
4. S. Weinberg, *Phys. Rev. Lett.* **37**, 657 (1976).
5. R. Rattazzi, *Zeit. für Physik* **C40**, 605(1988).
6. W. Bernreuther, U. Löw, J.P. Ma, and O. Nachtmann, CERN preprint CERN–TH.5113/88, to be published in Proc. of the "Heavy flavors" workshop, Erice 1988.
7. W. Bernreuther, U. Löw, J. P. Ma, and O. Nachtmann, Heidelberg preprint HD–THEP–88–26 (1988), to be published in *Zeit. für Physik* **C**.
8. L. Stodolsky, *Phys. Lett.* **150B**, 221 (1985).
9. F. Hoogeveen and L. Stodolsky, *Phys. Lett.* **212B**, 505 (1988).
10. J. Donoghue and G. Valencia, *Phys. Rev. Lett.* **58**, 451 (1987); Erratum *Phys. Rev. Lett.* **60**, 243 (1988).
11. P. Méry, M. Perrottet, and F. M. Renard, *Zeit. für Physik* **C38**, 579(1988).
12. M.B. Gavela, F. Iddir, A. Le Yaouanc, L. Oliver, P. Pène, and F.C. Raynal, *Phys. Rev.* **D39**, 1870 (1989).
13. J. Chauveau, in: "Physics at LEP", ed. by J. Ellis and R. Peccei, CERN–Yellow–Report, CERN 86–02 (1986), p. 177.
14. W. Bernreuther and O. Nachtmann, to be published.
15. C. Busch, DESY preprint, DESY 88–148 (1988).

16. G. Gamberini and G. Ridolfi, *Nucl. Phys.* **B287**, 304 (1987).

17. F.Gabbiani, F. H. Kim and A. Masiero, *Phys. Lett.* **214B**, 398 (1988).

18. B. Mukhopadhyaya and A. Raychaudhuri, *Phys. Rev.* **D39**, 280 (1989).

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