CP Violation at Low and High Energies*†

Bruce H. J. McKellar‡1

[1]School of Physics and Research Centre for High Energy Physics, University of Melbourne, Parkville Vie 3052, Australia

CP violation has yet to become a comfortable part of our understanding of the interaction of the elementary particles, in the way that P violation has. In part this may be because we do not yet have enough experimental information on CP violation to constrain the interaction phenomenologically, and still have too many viable models available. I will describe several ways of using low and high energy physics to constrain the interaction responsible for CP violation.

PACS Indices: 11.30.Er (Charge conjugation, parity, time reversal, and other discrete symmetries); 13.40.Em (Electric and magnetic moments); 12.6O.Fr (Extensions of electroweak Higgs sector).

1 Prologue

I have decided to reprint in this issue of the Universe in commemoration of the life Ernest Henley my paper on the occasion of his 70th birthday. But I want to preface it with some more memories of Ernest. As a graduate student I found his 1962 book with Walter Thirring *Elementary Quantum Field Theory* to be a wonderful help in my efforts to learn that subject, and its chapter on the lee model, a rare exactly solvable renormalisable field theory was so instructive it still has a place in my fading memories. His books on Subatomic Physics and Nuclear and Particle Physics were books I suggested as further reading when I was teaching those subjects.

Ernest and I had overlapping interests in the physics of parity violation in nuclei and in CP violation. He was Dean of the College of Arts and Sciences at the University of Washington from 1979 to 1987. A little later I was Dean of Science at Melbourne and I found him to be a very useful source of advice at that time.

I learned a lot of physics and a lot of insight into the organisation of Science for Ernest. That was a great privilege. In recognition of his contribution to my physics and my career, I dedicate this republication of my paper on *CP Violation at Low and High Energies* to his memory.

2 Introduction

It is a pleasure and a privilege to contribute to this First Symposium on Symmetries in Subatomic physics in honour of Professor Ernest Henley's 70th Birthday, because this subject has seen many important contributions from Ernest over his long career as a physicist. All of us who work in this field have been greatly influenced by him.

In this paper I will emphasise the recent contributions of the Melbourne Group to the study of CP vioaltion. The other group members are Dr. Xiao-Gang He, Dr. Jiang-Pen Ma, and Mr. Arthur Sakellariou. I am glad to acknowledge their vital contributions to our collaborative work.

By the CPT theorem, CP violation implies T violation. That nature is not symmetric under time reversal came as quite a surprise. Perhaps the best way to gauge that surprise is by looking at the feelings of physicists before the years 1956-1964, which are nicely summarised by a remark by Eddington in 1929:

> The Laws of Nature are indifferent as to the direction of time. There is no more distinction between past and future than between left and right.

*Refereed version of the invited paper presented at the First International Symposium on Symmetries in Subatomic Physics, May 16-18, 1994, Taipei, Taiwan, R.O.C.

†This article has been published in Chinese Journal of Physics **32** (6-II), 933-945 (1994).

‡Email: mckellar@tauon.ph.unimelb.edu.au

As we learned more about weak interactions, we realised that nature did indeed make a distinction between left and right, and between past and future [1, 2, 3, 4]. However, while the violation of parity invariance was rapidly incorporated into the mainstream picture of weak interactions, and now is an integral part of the standard model, T (or CP) violation has remained on the edge of our understanding.

The standard model does incorporate CP violation through the intrinsic phase in the KM matrix [5], which is intimately linked to the existence of 3 generations. The CP violating phase is then just another parameter of the standard model, and is thus no more calculable than, say, the top quark mass. Were this to be the case our understanding of CP violation at a fundamental level will be delayed until we discover the theory to which the standard model is the low energy effective field theory approximation.

On the other hand it is entirely possible that the origin of CP violation is in some non-standard physics – many possible explanations have been proposed, including

- Left-Right models
- Multi-Higgs models
- Supersymmetry

In any discussion of CP violation in flavour-conserving processes, we must remain alert to the possibility that CP violation will occur in the strong interactions through the so-called θ term in the QCD lagrangian,

$$\mathcal{L}_\theta = -\theta\frac{\alpha_s}{8\pi}\tilde{G}_{\mu\nu a}G_{\mu\nu a}. \tag{1}$$

This term is manifestly flavour conserving, and so ca.nnot contribute to CP violation in the $K^0\bar{K}^0$ system, but it can contribute to the electric dipole moment of the neutron, and other $\Delta F = 0$ CP violating effects.

In the $K^0\bar{K}^0$ system, the CP violating decays

$$\begin{aligned} K_L^0 &\rightarrow \pi^+\pi^-, \quad \text{and} \\ K_L^0 &\rightarrow \pi^0\pi^0 \end{aligned}$$

have been observed with the amplitudes η^{+-} and η^{00} respectively, relative to the corresponding CP allowed K_S^0 decay amplitude. Experimentally both η^{+-} and η^{00} are of order of magnitude 10^{-3}, and the difference between them is zero at the few tenths of a percent level. Theoreticians prefer to describe these amplitudes in terms of two other complex numbers, ϵ and ϵ'. The amplitude ϵ measures the CP violating mixing between K^0 and $\bar{K}^0$, a $\Delta S = 2$, or superweak process, while ϵ' measures the "direct" CP violation in the amplitude for $K_2^0 \rightarrow 2\pi$. (K_2^0 is the CP-odd eigenstate of the $K^0\bar{K}^0$ system.)

The relationship between the amplitudes is

$$\begin{aligned} \eta^{+-} &= \epsilon + \epsilon' \\ \eta^{00} &= \epsilon - 2\epsilon'. \end{aligned} \tag{2}$$

The present experimental measurements are [6],

$$\mathrm{Re}(\epsilon'/\epsilon) = \begin{cases} (23 \pm 6.5) \times 10^{-4}, & \text{NA31} \\ (7.4 \pm 6.0) \times 10^{-4}, & \text{E731} \end{cases}. \tag{3}$$

While the result of NA31 indicates a non-zero ϵ'/ϵ, the value of E731 is compatible with zero. Nevertheless the results are mutually consistent at 2σ level, and the mean result is expressible as

$$\mathrm{Re}(\epsilon'/\epsilon) \leq 3 \times 10^{-3} \text{ at } 95\% \text{ C.L.} \tag{4}$$

While the Kaon system is the only system in which CP violation has been observed, it is still possible to obtain useful information about some of the possible interactions from it, as we will see in the next section. However the real opportunity for understanding CP violation is in the possibility that we can make observations on other systems, and so develop a phenomenology of the CP violating intera.ction. Much work has been done on what can be found out from the B-meson system, and that is reviewed in other papers presented to this Symposium.

I will review our recent work on

(1) The contribution of anomalous triple boson couplings to ϵ'/ϵ.
(2) Information available from limits on the electric dipole moments of the neutron and of atoms.
(3) Tests of CP violation with a photon collider.

3 Anomalous Triple Boson Couplings and ϵ'/ϵ

It is well known that the penguin diagram contributes to the direct CP violating amplitude ϵ'. The original estimates were that $\epsilon'/\epsilon \approx 10^{-2}$, but the inclusion of the electroweak penguim diagrams and a more sophisticated calculation [7, 8] reduced the prediction to $\epsilon'/\epsilon \approx 10^{-3}$ to 10^{-4}. The value of ϵ'/ϵ is a sensitive function of the top quark mass and has a zero at $m_t \approx 220$ GeV.

What does not seem to have been widely appreciated is that the value of ϵ'/ϵ is not just a probe of CP violating physics in the standard model and beyond, but it also probes other, *non-CP-violating*, physics. Examples of this are the anomalous couplings of three vector bosons, which can be induced by radiative corrections in the sta.ndard model and in other models, and which can significantly alter the value of ϵ'/ϵ from the standard model value [9].

The most general WWV interactions with the W boson on shell, invariant under $U(1)_{em}$, can be parametrized as [10]

$$\begin{aligned}\mathcal{L}_V &= -ig_V \Big[\kappa^V W^+_\mu W^-_\nu V^{\mu\nu} \\ &+\frac{\lambda^V}{M_W^2} W^+_{\sigma\rho} W^{-\rho\delta} V^\sigma_\delta \\ &+g_1^V (W^{+\mu\nu} W^-_\mu - W^+_\mu W^{-\mu\nu}) V_\nu \\ &+g_4^V W^+_\mu W^-_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu) \\ &+\tilde{\kappa}^V W^+_\mu W^-_\nu \tilde{V}^{\mu\nu} + \frac{\tilde{\lambda}^V}{M_W^2} W^+_{\sigma\rho} W^{-\rho\delta} \tilde{V}^\sigma_\delta \\ &+g_5^V \epsilon_{\mu\nu\alpha\beta} (W^{+\mu} \partial^\alpha W^{-\nu} \\ &-\partial^\alpha W^{+\mu} W^{-\nu}) V^\beta \Big], \qquad (5)\end{aligned}$$

where $W^{\pm\mu}$ are the W boson fields; the fields V are the γ or Z fields, and the coefficients are superscriped appropriately; $W_{\mu\nu}$ and $V_{\mu\nu}$ are the W and V field strengths, respectively; and $\tilde{V}_{\mu\nu}$ is the dual to $V_{\mu\nu}$, *viz.* $\tilde{V}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\alpha\beta} V^{\alpha\beta}$. The terms proportional to κ, λ, and $g^Z_{1,5}$ are CP conserving and $\tilde{\kappa}$, $\tilde{\lambda}$ and g_4^Z are CP violating. For $V = \gamma$, $G_V = e$ and for $V = Z$, $g_V = g\cos\theta_W$. $g_\gamma g_1^\gamma$ is the W boson charge, e, so g_1^γ. In the standard model at the tree level, $\kappa^V = 1$, $g_1^Z = 1$, and all other couplings in Eq. (1) (except $g_1^\gamma = 1$) are zero. The anomalous gauge boson couplings are $\Delta\kappa^V = \kappa^V - 1$, $\Delta g_1^Z = g_1^Z - 1$, g_4^V, $\tilde{\kappa}^V$, $\tilde{\lambda}^V$, and g_5^V.

The CP violating anomalous couplings, $\tilde{\kappa}^V$, $\tilde{\lambda}^V$, and g_5^V, contribute to ϵ'/ϵ at higher order in the weak interaction, and can be neglected. The CP conserving anomalous couplings $\Delta\kappa^V = \kappa^V - 1$, $\Delta g_1^Z = g_1^Z - 1$, and g_4^V change the electroweak penguin contribution, but, as they require the presence of three electroweak bosons in the diagram do not affect the gluon penguin. Since ϵ'/ϵ is the net effect of contributions from the electroweak penguin and the gluon penguin, which tend to cancel each other, we would expect that relatively small modifications of the former induced by the anomalous couplings would have a significant effect on the value of ϵ'/ϵ. That is bourne out by our calculation.

To obtain numerical estimates we need information about the possible magnitudes of the anomalous couplings, which can be constrained from a number of experiments. Collider experiments at high energies have put constraints on some of these couplings [11, 12], as have analyses of rare decays [13, 14, 15, 16, 17]. The constraints from rare decays are better than those obtained from the $g - 2$ of the muon [18]. The most stringent constraints on the anomalous gauge boson couplings are from oblique corrections to the precision electroweak experiments [19], but these corrections are quadraticly or even quarticly divergent. For this reason we regard the constraints from direct W pair productions [11, 12], and rare decays [15, 16] (where the divergences are at most logrithmic) as more reliable. For the CP violating anomalous coupling, the best constraints are from neutron and electron electric dipole moments [20].

Details of the calculation are given in Ref. [9]. The important point to emphasise is the ϵ'/ϵ can vary by as much as a factor of two and there is a substantial shift to the position of the zero as a function of m_t. When m_t is known with precision, and ϵ'/ϵ is finally measured, it may be possible to use the value of ϵ'/ϵ as a probe of the physics beyond the standard model.

4 Electric Dipole Moments of the Neutron and of Atoms

One of the classic tests of P and T violation is the search for an electric dipole moment of elementary particles. The transformation properties of the electric dipole moment $\boldsymbol{d}$, and the angular momentum $\boldsymbol{J}$, are

$$\begin{aligned}&\text{under } P: \quad \boldsymbol{d} \to -\boldsymbol{d} \quad \boldsymbol{J} \to \boldsymbol{J} \\ &\text{under } T: \quad \boldsymbol{d} \to \boldsymbol{d} \quad \boldsymbol{J} \to -\boldsymbol{J}. \qquad (6)\end{aligned}$$

But, by the Wigner-Eckart theorem,

$$\boldsymbol{d} = D\boldsymbol{J}, \qquad (7)$$

defining the electric dipole moment (EDM) D. It is thus clear that the observation of a non-zero value for D implies the violation of *both* P and T (or P and CP) symmetry.

Experiments have concentrated on the EDM of the neutron and of neutral atoms. The EDM of the atom is not simply the appropriate sum of the EDMs of the constitutents, although one can write the EDM of the neutron as a sum of the quark EDMs:

$$D_n = \frac{1}{3}(4)D_d - D_u, \tag{8}$$

at least in the non-relativistic quark model [21]. The difference lies in the fact that the forces in the atom are dominantly electrostatic. In fact if the atomic forces were purely electrostatic, and the charge and electric dipole distributions were identical, there would be no atomic EDM (to first order in the constituent EDMs), a result known as Schiff's theorem [22, 23]. The result can be illustrated by considering a single particle hamiltonian,

$$h_j = \frac{p_j^2}{2m_j} + e_j\phi(r_j) + \boldsymbol{d}_j \cdot \nabla\phi(r_j), \tag{9}$$

where $\phi(r_j)$ is the electrostatic potential at the position of the particle j, containing contributions from the other charges and EDMs as well as the external field. With

$$h_{0j} = \frac{p_j^2}{2m_j} + e_j\phi(r_j) \tag{10}$$

one can write the hamiltonian h_j as

$$\begin{aligned} h_j &= h_{0j} + i[\boldsymbol{d}_j \cdot \boldsymbol{p}_j, \phi(r_j) \\ &= e^{i\mathbf{d}_j\cdot\mathbf{p}_j/e_j} h_{0j} e^{-\mathbf{d}_j\cdot\mathbf{p}_j/e_j} + O(|d_j|^2)(11) \end{aligned}$$

Thus, neglecting terms of order $O(|d_j|^2)$, h_j and h_{0j} have the same spectrum, and there is no splitting of energy levels in the external electric field which would be produced by an atomic EDM.

The important feature of Schiff's paper is not that it proved the Schiff theorem, but that it identified the conditions under which the atom would have an EDM by specifying the conditions under which the theorem could be proved. Thus

- non-electrostatic interactions,
- relativistic corrections,
- a lack of proportionality of the EDM distribution and the charge distribution, and
- interactions between the electrons, between the electrons and nucleons, or between the nucleons, which violate P and T symmetry,

can all contribute to the atomic EDM.

To be explicit consider a situation in which the atom has an even Z but an odd N, so there is no electronic angular momentum, but there is a nuclear angular momentum. The atomic EDM, $D(^AZ)$, is a nuclear effect, but it is *not* determined by the nuclear EDM. Rather the P and T violating interaction between the nucleus and the atomic electrons is in the additional electrostatic potential

$$\delta\phi = 4\pi\boldsymbol{Q}\cdot\nabla\delta(\boldsymbol{r}), \tag{12}$$

where the Schiff moment $\boldsymbol{Q}$ is defined as

$$\boldsymbol{Q} = \frac{1}{10}\left\langle \sum_j (q_j\boldsymbol{r}_j + \boldsymbol{d}_j)\left\{r_j^2 - \frac{5}{3}\langle r^2\rangle_q\right\}\right\rangle. \tag{13}$$

^{199}Hg is an atom of this type for which there is a good experimental limit [24] on the atomic EDM,[1]

$$D(^{199}\text{Hg}) \leq 3\times10^{-14}\ \text{e.fm}. \tag{14}$$

As [25]

$$D(^{199}\text{Hg}) \approx 4\times10^{-4}\frac{|\boldsymbol{Q}|}{\text{fm}^2}, \tag{15}$$

we have a limit on the Schiff moment of ^{199}Hg,

$$|\boldsymbol{Q}(^{199}\text{Hg})| \leq 0.8\times10^{-10}\ \text{e.fm}. \tag{16}$$

What does this tell us about the underlying P and T violating interaction? Rather than work at the quark level let us work at the hadronic level, where one would expect interactions involving meson loop contributions to the nucleon EDM, and P and T violating meson exchange interactions between the nucleons to be the major contributions to the nuclear Schiff moment.

Fortunately the T and P violating MNN interactions are rather simpler than the P violating MNN interactions which are perhaps more

[1] As the size of hadrons is about 1 fm, I prefer to quote the EDM in e.fm, rather than the more usual e.cm. The choice of e.fm give a feeling for the degree of supression of the EDM below the natural scale because of the weakness of the P and T violating interaction.

familiar. In the latter case it is well known that the vector mesons, the ρ and the ω, are as important as the π. But in the present case a careful analysis of the P and T violating interactions at the QCD level [27] showed that the $NN\pi$ interactions dominate.

Phenomenlogically one may write

$$\mathcal{L}_{\pi NN} = \bar{\psi}\{g\gamma_5 + \bar{g}\}\tau\psi \cdot \phi, \tag{17}$$

where I have, for simplicity, omitted terms corresponding to $\Delta I = 1$ and $\Delta I = 2$ CP violating interactions.

An effective one nucleon interaction generated from the P and T violating NN interactions gives

$$|\boldsymbol{Q}| \approx \left|\frac{3}{80}\frac{eg\bar{g}}{m_N r_0}\frac{1}{m_\pi^2 U(0)} A^{\frac{2}{3}}\right|, \tag{18}$$

where $r_0 A^{\frac{2}{3}}$ is the nuclear radius and $U(0)$ is the shell model potential at the origin. This gives

$$|g\bar{g}| \lesssim 10^{-9}. \tag{19}$$

However the same interaction gives

$$d_n \approx \frac{eg\bar{g}}{4\pi^2 m_N} \ln\left(\frac{m_N}{m_\pi}\right) \tag{20}$$

as the neutron EDM, and the experimental limit

$$|d_n| \leq 10^{-12} \text{ e.fm} \tag{21}$$

limits the product of the coupling constants to

$$|g\bar{g}| \lesssim 10^{-10}. \tag{22}$$

The atomic EDM, at the present level of accuracy, is thus not quite as stringent a limit on the $NN\pi$ coupling constants as the neutron EDM, but the technology is improving rapidly and one can expect the atomic measurements to approach the sensitivity of the neutron measurements in the near future.[2]

Already, with the present limits the are important restrictions that can be placed on the CP violating parameters at the level of quarks, gluons and electorweak bosons [28]. For example the θ parameter of QCD is limited to be less than 10^{-9}.

[2] The paper by W Haxton reported an improved calculation of the relationship between $\boldsymbol{Q}$ and $\bar{g}$, which shows that the present experimental limit on $D(^{199}\text{Hg})$ actually gives a tighter limit on $\bar{g}$ than does the limit on d_n.

5 CP Violation at a Photon Collider

At very high energies, such as those at the NLC with $\sqrt{s} \approx 500$ GeV, the cross-section for $e^+e^- \to W^+W^-$ decreases rapidly, and the production of W^+W^- pairs may be more efficient through the process $\gamma\gamma \to W^+W^-$. It has been proposed that the electron-electron collider be converted to a photon-photon collider by Compton scattering the electrons from the photons in a laser. In this way an intense beams of very high energy photons can be created, and collided to produce W^+W^- and $t\bar{t}$ pairs. It is then an obvious question to ask what experiments can be done to look for CP violation in the processes $\gamma\gamma \to W^+W^-$ and $\gamma\gamma \to t\bar{t}$. Part of the motivation for the question is the observation that a number of the mechanisms suggested for CP violation become more effective at high energies, or when particles of a large mass are involved. The gives rise to the hope that one can limit the CP violating interaction from these processes although the cross-section is in the 10 pb range.

Take as an example [29] the process $\gamma\gamma \to W^+W^-$. The W particles decay with a branching ratio of approximately 33% to $\ell\nu$, so we look at the process

$$\gamma\gamma \to \begin{cases} W^+ & \to \ \ell^+\nu_\ell \\ W^- & \to \ \ell^-\bar{\nu}_\ell \end{cases} \tag{23}$$

We want to construct CP violating observables which do not require the observation of any of the polarisations of the particles involved. Such observables are

$$\mathcal{O}_1 = \frac{E_+ - E_-}{m_W}, \tag{24}$$

$$\mathcal{O}_2 = (\hat{\boldsymbol{p}} \cdot \hat{\boldsymbol{q}}_+)^2 - (\hat{\boldsymbol{p}} \cdot \hat{\boldsymbol{q}}_-)^2, \tag{25}$$

$$\mathcal{O}_3 = [\hat{\boldsymbol{p}} \cdot (\hat{\boldsymbol{q}}_+ - \hat{\boldsymbol{q}}_-)][\hat{\boldsymbol{p}} \cdot (\hat{\boldsymbol{q}}_+ \times \hat{\boldsymbol{q}}_-)]. \tag{26}$$

Here $\boldsymbol{p}$ is the photon 3-momentum, and $(E_\pm, \boldsymbol{q}_\pm)$ is the 4-momentum of the $\ell^\pm$, all measurements being made in the laboratory frame, which is also the c.m. frame for the photons.

Experimentally one can determine either $\langle \mathcal{O}_i \rangle$ or the asymmetry

$$A_i = \frac{N(\mathcal{O}_i > 0) - N(\mathcal{O}_i < 0)}{N(\mathcal{O}_i > 0) + N(\mathcal{O}_i < 0)}. \tag{27}$$

In the process we are studying the effect of CP violation from the minimal standard model is zero up to two loop level at least and is thus too small to be observed. We consider two Higgs-doublet extensions of the minimal standard model. In these extensions CP violation is due to the complex expectation values of the Higgs-doublets.The effect of CP violation from these extensions has been studied in top quark decay [30] and in the $t\bar{t}$ system produced at pp colliders [31] or at e^+e^- [32, 33] colliders, where CP asymmetries can be large as 10^{-3}. CP violation in the interactions between the gauge bosons is also studied in Refs. [34, 35]. The process considered here gives another oppertunity to study CP violation in such extensions.

CP violation in these processes can be obtained at one loop level throughthe process $\gamma\gamma \to f\bar{f} \to$ Higgs $\to W^+W^-$. At this level the CP violation is caused by CP violation in the subprocess $f\bar{f} \to$ Higgs, and the heaviest fermion is dominant. In the following we will take only the top quark into account and employ the notation used in Refs. [34, 35]. In this notation CP violation due to the neutral Higgs exchange is paramerized with a 3×3 real othogonal matrix d, the nonzero off diagonal matrix elements d_{3j} and d_{j3} $(j = 1, 2)$ indicating CP violation. The couplings involved are:

$$\begin{aligned}\mathcal{L}_{int} &= e\frac{m_t}{2M_W \sin\theta_W}\text{ctg}\beta d_{3j}\phi_j\bar{t}i\gamma_5 t \\ &-i\frac{2}{3}e\bar{t}\gamma_\mu t A^\mu \\ &+e\frac{M_W}{\sin\theta_W}d_{1j}\phi_j W_\mu^+ W^{-,\mu}, \qquad (28)\end{aligned}$$

where ϕ_j $(j = 1, 2, 3)$ are the mass eigenstates of the neutral Higgs fields, $\text{ctg}\beta = \upsilon_2/\upsilon_1$ is the ratio of the absolute expectation values of the two Higgs-doublets. We assume that the ϕ_1 is the lightest Higgs particle and dominates, giving the CP violating amplitude T_A:

$$\begin{aligned}T_A &= \frac{16}{3}\frac{\alpha^2}{\sin\theta_W^2}\text{ctg}\beta \\ &d_{11}d_{31}I\left(\frac{\sqrt{\hat{s}}}{2m_t}\right)D_H(\hat{s}, M_H) \\ &\cdot\varepsilon^{\nu_1}(p_1)\varepsilon^{\nu_2}(p_2)\varepsilon^*_{\mu_1}(k_1) \\ &\varepsilon^*_{\mu_2}(k_2)g^{\mu_1\mu_2}\varepsilon_{\nu_1\nu_2\alpha\beta}p_1^\alpha p_2^\beta \qquad (29)\end{aligned}$$

with

$$\begin{aligned}\hat{s} &= (p_1 + p_2)^2 \\ I(z) &= \left\{\begin{array}{l}\frac{1}{2z^2}(\arcsin(z))^2, \\ \frac{1}{2z^2}\left(\frac{\pi}{2} + \frac{i}{2}\ln\frac{z+\sqrt{z^2-1}}{z-\sqrt{z^2-1}}\right)^2,\end{array}\right. \\ &\quad \begin{array}{l}\text{for } z \le 1 \\ \text{for } z > 1\end{array}. \qquad (30)\end{aligned}$$

Here M_H stands for the mass of ϕ_1 and D_H is its propaga.tor. The CP violating part of the quantity R defined above is then obtained through the interference between T_A and the amplitude for the process $\gamma\gamma \to W^+W^-$ at the tree-level in the standard model.

In the expression for T_A the coupling parameters $\text{ctg}\beta$ and $d_{11}d_{13}$ are unknown. From the upper bound of the electric dipole moment of the neutron one cannot obtain enough information to constrain $d_{11}d_{13}$. From the fa.ct that the d is a 3×3 real othogonal matrix an upper bound can be derived:

$$d_{11}d_{13} \le \frac{1}{2}$$

As to the ratio $\text{ctg}\beta$ certain discrete symmetries may 1ead to the so called "natural choice", $\text{ctg}\beta < 1$, based on the observation that $m_t >> m_b$. However, not all discrete symmetries, which can be imposed on the theory to eliminate the flavour changing neutral currents at tree level, lead to $\text{ctg}\beta < 1$, for example, the models I and III listed in Ref. [32] allow $\text{ctg}\beta > 1$. It is possible that the ratio $\text{ctg}\beta$ may be larger than one.

It is important to emphasise that the absorptive part of the Higgs propagator, which can be significant for $M_H > 2M_W$, plays an important role in the calculations. The width Γ_H, which depends on unknown parameters, is expected to be reasonably small for $M_H < 2m_t$. In this region one may guess $0 \le \Gamma_H \le 40$ GeV, and for these values we find a narrow width approximation to the propagator is adequate. For $M_H > 2m_t$ one may expect $\Gamma_H > 100$ GeV, and the narrow width approximation is no longer adequate, results for our observables varying by 50% or so.

Typical numerical results are For $M_H = 100$ GeV:

$$\begin{aligned}A_1 &= 1.36 \times 10^{-4}d_{11}d_{31}\text{ctg}\beta, \\ \langle O_1\rangle &= 1.46 \times 10^{-4}d_{11}d_{31}\text{ctg}\beta, \\ A_3 &= 1.68 \times 10^{-4}d_{11}d_{31}\text{ctg}\beta, \\ \langle O_3\rangle &= 6.5 \times 10^{-5}d_{11}d_{31}\text{ctg}\beta, \qquad (31)\end{aligned}$$

and for $M_H = 500$ GeV:

$$\begin{aligned} A_1 &= -1.35 \times 10^{-4} d_{11} d_{31} \mathrm{ctg}\beta, \\ \langle O_1 \rangle &= -1.53 \times 10^{-4} d_{11} d_{31} \mathrm{ctg}\beta, \\ A_3 &= -1.27 \times 10^{-4} d_{11} d_{31} \mathrm{ctg}\beta, \\ \langle O_3 \rangle &= -4.48 \times 10^{-5} d_{11} d_{31} \mathrm{ctg}\beta. \end{aligned} \quad (32)$$

Assuming a luminosity in the $\gamma\gamma$ collider of 10 fb^{-1} per year one can estimate a, statistical error of a few tenths of a percent for these observables in a years running. This suggests that $d_{11} d_{31} \mathrm{ctg}\beta$ should be larger than about 10 to be detectable in a reasonable time. Of course, other possible CP violating observables become accessible if the $\gamma\gamma$ collider has a polarised photon capability.

Details of the calculations described in this section are give in Ref. [29].

6 Conclusion

CP violation could simply be a phenomenon of the standard model, determined in magnitude by the complex phase in the KM matrix, which is itself no more mysterious than the other arbitrary parameters of the model. However there is the more exciting possibility that it is the signal of physics beyond the standard model. That possibility drives the calculations I have described above, and the calculations that many other speakers at this symposium have described.

I hope that, when we gather to celebrate Ernest's 8Oth birthday, we will have at last identified the source of CP violation!

Acknowledgments

Dedicated to Professor Ernest Henley on the occasion of his 7Oth Birthday. Supported in part by the Australian Research Council under grant number A69330949.

References

[1] T. D. Lee and C. N. Yang, Phys. Rev. **104**, 254 (1956).

[2] C. S. Wu, E. A mbler, R. W. Heyward, D. D. Hoppes, and R. P. Hudson, Phys. Rev. **105**, 1413 (1957).

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

[4] C. N. Yang, *these proceedings*.

[5] M. Robayashi and T. Maskawa, Prog. Thoer. Phys. **49**, 652 (1973).

[6] A. Wagner (NA31), Talk presented at the European Physics. Symp., Marseille (July 1993); L. K. Gibbons *et al.* (E731), Phys. Rev. Lett. **70**, 203 (1993).

[7] J. M. Flynn and L. Randall, Phys. Lett. **B224**, 221 (1989); Erratum: **B235**, 412 (1990); E. A. Paschos and Y. L. Wu, Mod. Phys. Lett. **A6**, 93 (1991); M. Lusignoli, L. Maiani, G. Martinelli, a.nd L. Reina, Nucl. Phys. **B369**, 139 (1992).

[8] G. Buchalla, A. J. Buras, and K. M. Harlander, Nucl. Phys. **337**, 313 (1990).

[9] X.-G. He and B. H. J. McKellar, preprint OITS-541, UM-P-94/47 from the University of Oregon and the University of Melbourne, May 1994.

[10] K. J. F. Gaemers and G. Gounaris, Z. Phys. **C1**, 259 (1979); K. Hagiwara, K. Hikasa, R. D. Peccei, and D. Zppenfeld, Nucl. Phys. **B282**, 253 (1987).

[11] J. Alitti *et al.*, Phys. Lett. **B277**, 194 (1992).

[12] M. Samuel *et al.*, Phys. Lett. **B280**, 124 (1992).

[13] S.-P. Chia, Phys. Lett. **B240**, 465 (1990).

[14] K. A. Peterson, Phys. Lett. **B282**, 207 (1992); K. Namuta, Z. Phys. **C52**, 691 (1991).

[15] Xiao-Gang He and B. McKellar, Phys. Lett. **B320**, 165 (1994); T. G. Rizzo, Preprint, ANL-HEP-PR-93-19; U. Baur, Preprint FSU-HEP-930719.

[16] Xiao-Gang He, Phys. Lett. **B319**, 327 (1993).

[17] S. Dawson and G. Valencia, Preprint, Fermilab-Pub-93/218-T; G. Baillie, Preprint, UCLA/93/TEP/26.

[18] A. Grau and J. A. Grifols, Phys. Lett. **B154**, 283 (1985); J. C. Wallet, Phys. Rev. **D32**, 813 (1985).

[19] C. P. Burgess and D. London, Phys. Rev. Lett. **69**, 3428 (1992); C. P. Burgess, S. Godfrey, H. Koning, D. London, and I. Maksymyk, Preprint, McGill-93/14, UdeMLPN- TH-93-154, OCIP/C-93-7; A. De Rujula, M. B. Gavela, P. Hernadez, and E. Masso, Nucl. Phys. **B384**, 3 (1992); K.

Hagiwara, S. Ishihara, R. Szalapski, and D. Zeppenfeld, Phys. Lett. **B283**, 353 (1992); Preprint, MAD/PH/737 (1993); P. Hernadez and F. J. Vegas, Phys. Lett. **B307**, 116 (1993).

[20] W. Marciano and A. Queijeiro, Phys. Rev. **D33**, 3449 (1986); A. De Rujula, M. Gavela, O. Pene, and F. Vegas, Nucl. Phys. **B357**, 311 (1991); F. Boudjema, K. Hagiwara, C. Hamzaoui, and K. Numata, Phys. Rev. **D43**, 2223 (1991); F. Boudjema, C. Burges, C. Hamzaoui, and J. Robinson, Phys. Rev. **D43**, 3683 (1991).

[21] See J. P. Costella, 4th Year report, University of Melbourne, 1991 for a discussion of relativistic effects in this process.

[22] L. I. Schiff, Phys. Rev. **132**, 2194 (1963).

[23] E. N. Purcell and N. F. Ramsey, Phys. Rev. **78**, 807 (1950).

[24] J. P. Jacobs, W. M. Klipstein, S. K. Lamoreaux, B. R. Heckel, and E. N. Fortson, Phys. Rev. Lett. **71**, 3782 (1993).

[25] V. V. Flambaum, I. B. Khriplovich, and O. P. Sushkov, Phys. Lett. **B162**, 213 (1985).

[26] V. V. Flambaum, I. B. Khriplovich, and O. P. Sushkov, Nucl. Phys. **A449**, 750 (1986).

[27] V. P. Gudkov, X.-G. He, and B. H. J. McKellar, Phys. Rev. **C47**, 2365 (1993).

[28] X.-G. He, B. H. J. McKellar, and S. Pakvasa, Int. J. Mod. Phys. **A4**, 5011 (1989); Erratum **A6**, 1063 (1991).

[29] J. P. Ma and B. H. J McKellar. Phys. Lett. **B319**, 533 (1993).

[30] B. Grzadkowski and J. F. Gunion, Phys. Lett. **B287**, 237 (1992).

[31] C. R. Schmidt and M. Peskin, Phys. Rev. Lett. **69**, 410 (1992).

[32] W. Bernreuther, T. Schröder, and T. N. Pham, Phys. Lett. **B279**, 389 (1992).

[33] W. Bernreuther, O. Nachtmann, P. Overmann, and T. Schröder, Nucl. Phys. **B388**, 53 (1992).

[34] A. Méndez and P. Pomarol, Phys. Lett. **B272**, 313 (1991).

[35] X. G. He, J. P. Ma, and B. H. J. McKellar, Phys. Lett. **B304**, 285 (1993).