CP VIOLATION IN WEAK DECAYS AND ELSEWHERE

Werner Bernreuther

Institut f. Theoretische Physik, RWTH Aachen, D-52056 Aachen, Germany

Abstract:
A brief overview is given on the status and prospects of searches for CP non-conservation effects in weak decays of strange, charmed, and beauty hadrons, on the search for permanent electric dipole moments of particles, and on present and future high energy CP tests at colliders.

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1 Introduction

The origin of CP nonconservation remains one of the few dark corners of the theory of electroweak interactions. Another one is the dynamics of electroweak symmetry breaking. Very probably these two corners are related: clarification of weak gauge symmetry breaking would also shed light on the origin of CP violation. More pragmatically speaking, we do not know so far whether this symmetry violation arises from a single “source” – which is most likely the Kobayashi-Maskawa (KM) phase \( \text{I} \) in the charged weak quark currents – or whether there are several CP-nonconserving interactions which will show up in different physical situations.

There are a number of well-known reasons which motivate the belief that the Standard Model (SM) is part of a larger gauge theory. Extensions of the SM almost invariably entail a larger non-gauge sector – i.e., scalar self interactions and Yukawa interactions – than the SM.\(^2\) In this way quite a number of “new” CP-violating (CPV) interactions\(^3\) for quarks and for leptons are conceivable in a natural way. In particular CPV interactions with the following features may exist: Interactions that are unrelated to the mixing of quark generations and the hierarchy of quark masses. Well known examples include CPV by an extended scalar Higgs sector \([2, 3]\) and CPV phases in soft supersymmetry (SUSY) breaking terms. Such sources can induce also sizable CP effects in flavour diagonal interactions. Specifically, interactions involving Higgs bosons can induce effects which drastically grow with some power of a fermion mass, thus leading to potentially large effects in the heavy flavour sector. So far the only hint for CPV beyond the KM phase are recent attempts to develop scenarios for explaining the baryon asymmetry of the universe \([8, 9]\).

In the following a number of CPV laboratory phenomena due to the KM phase and some non-KM sources of CP violation are discussed. (We shall not deal with the strong CP problem; for a recent review, see \([10]\).)

2 Weak Decays

Observable CP violation à la KM requires quarks whose weak decays are Cabibbo suppressed. That is not the case for \( c \) and \( t \) quarks. Therefore CP searches involving these quarks will predominantly test for new interactions.

2.1 Kaons and Hyperons

The KM mechanism can account for the observed CP violation in \( \Delta S = 2 \) \( K^0 - \bar{K}^0 \) mixing. The present experimental status on “direct” \( \Delta S = 1 \) CP violation in \( K^0 \rightarrow 2\pi \) is inconclusive \([11, 12]\). New experiments aim at measuring \( \text{Re}(\epsilon')/\epsilon \) at the level of \( 10^{-4} \). On the theoretical side considerable

\(^2\)For a recent review of CPV in the context of dynamical symmetry breaking, see \([7]\).

\(^3\)In the following, new CP-violating interactions refer to interactions not due to the KM phase.
effort has ben spent over the last years to calculate the next-to-leading order QCD corrections to the effective weak Hamiltonian within the SM, to pursue various approaches in determining weak matrix elements, and to get a handle on the various uncertainties involved in the prediction of $\epsilon'/\epsilon$. A recent detailed review [13] of the current status estimates this quantity within the SM $\sim a \ few \times 10^{-4}$.

Hyperon decays also offer a possibility to establish CP violation in $\Delta S = 1$ decays. Consider for instance the decay of polarized $\Lambda \to p\pi^-$ and $\bar{\Lambda} \to \bar{p}\pi^+$. The differential decay distributions are proportional to $(1 + \alpha_\Lambda \vec{\omega}_\Lambda \cdot \hat{p}_p)$ and $(1 + \alpha_{\bar{\Lambda}} \vec{\omega}_{\bar{\Lambda}} \cdot \hat{p}_{\bar{p}})$, respectively, where $\vec{\omega}$ is the hyperon polarization vector and $\hat{p}$ is the (anti) proton direction of flight in the hyperon rest frame. The spin analyser quality factor $\alpha$, which is parity-violating, is generated by the interference of S and P wave amplitudes. CP invariance requires that $\alpha_\Lambda = -\alpha_{\bar{\Lambda}}$. Hence a CP observable is

$$A_\Lambda = \frac{\alpha_\Lambda + \alpha_{\bar{\Lambda}}}{\alpha_\Lambda - \alpha_{\bar{\Lambda}}}.$$  

Note that $A_\Lambda$ is CP-odd but T-even, i.e., even under the reversal of momenta and spins. Hence a non-zero asymmetry (1) requires, apart from CP phases, also absorptive parts in the amplitudes. Neglecting isospin $I = 3/2$ contributions, an approximate expression for $A_\Lambda$ is given by (see, for instance ref. [14])

$$A_\Lambda \simeq -\tan(\delta_{1/2}^P - \delta_{1/2}^S) \sin(\varphi_{1/2}^P - \varphi_{1/2}^S),$$  

where $\delta_{1/2}^{S,P}$ and $\varphi_{1/2}^{S,P}$ are the S,P wave final state phase shifts and weak CP phases for the isospin $I = 1/2$ amplitudes, respectively.

In the Standard Model CP violation in $\Delta S = 1$ hyperon decays is induced by penguin amplitudes. Extensions of the SM may add charged Higgs penguin, gluino penguin contributions, etc. Predictions for hyperon CP observables like $A_\Lambda$ are usually obtained [15–17] as follows: within a given model of CP violation one computes first the effective weak $\Delta S = 1$ Hamiltonian at the quark level. (In the SM its next-to-leading order QCD corrections are known [13].) The strong phase shifts $\delta_{1/2}^{S,P}$ are extracted from experimental data. The usual strategy in determining the weak phases $\varphi_{1/2}^{S,P}$ is to take the real parts of the matrix elements $<\pi p|H_{eff}|\Lambda>_{I=1/2}^{S,P}$ from experiment, whereas the CPV part is computed using various models for hadronic matrix elements. Although the theoretical uncertainties are quite large one may conclude [15,17] from these calculations that within the SM the asymmetry $A_\Lambda$ is about $4 \times 10^{-5}$. Contributions from non SM sources of CP violation can yield larger effects, but are constrained by the $\epsilon'$ and $\epsilon$ parameters from $K$ decays. He and Valencia conclude that $|A_\Lambda^{non-SM}|$ cannot exceed $a \ few \times 10^{-4}$.

A high statistics hyperon experiment [18] (E871) at Fermilab is underway. The decay chain $\Xi^- \to \Lambda\pi^- \to p\pi^+\pi^-$ and the corresponding decay chain for $\bar{\Xi}^+$ will be used. They $\Xi$’s will be produced unpolarized. Then the $\Lambda$ polarization is given by $\vec{\omega}_\Lambda = \alpha_\Xi \hat{p}_\Lambda$, where $\hat{p}_\Lambda$ is the $\Lambda$ direction of flight in the
Ξ rest frame. E871 measures the asymmetry

\[ A = \frac{\alpha_\Lambda \alpha_\Xi - \alpha_\Lambda \bar{\alpha}_\Xi}{\alpha_\Lambda \alpha_\Xi + \alpha_\Lambda \bar{\alpha}_\Xi} \simeq A_\Lambda + A_\Xi. \] (3)

\( A_\Xi \) is estimated to be smaller than \( A_\Lambda \) because of smaller phase shifts. E871 expect to produce about \( 10^9 \) events. They aim at a sensitivity \( \delta A \simeq 10^{-4} \). If an effect will be observed at this level it will be, in view of the above, most probably of non SM origin.

2.2 Charm

\( D^0 - \bar{D}^0 \) mixing and associated CP violation in the \( \Delta C = 2 \) mixing amplitude, and direct CP violation in the \( \Delta C = 1 \) charm decay amplitudes are predicted to be very small in the SM.

In the SM direct CPV may be significant only for singly Cabibbo suppressed decays. In this case one has at the quark level two contributions to the decay amplitude, namely the usual “tree” amplitude and the penguin amplitude, that have different weak phases. At the hadron level the decay amplitude is of the form \( A e^{i \delta_A} + B e^{i \delta_B} \), where \( \delta_{A,B} \) are strong interaction phase shifts. This leads to a CP asymmetry

\[ A_D = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})} \propto \text{Im}(AB^*) \sin(\delta_B - \delta_A). \] (4)

Buccella et al. [20] have investigated \( A_D \) within the SM for a number of Cabibbo suppressed channels. They calculated the strong phase shifts for the respective channels by assuming dominance of the nearest resonance. For some modes, for instance \( D^+ \to K^{*0} K^+ \) and \( D^+ \to \rho^+ \pi^0 \) they find \( A_D \sim 10^{-3} \). In some extensions of the SM like non-minimal supersymmetry [21] or left-right-symmetric models [22] \( A_D \) can be larger by about one order of magnitude. Moreover, asymmetries of the same order could also be generated in these models for Cabibbo allowed and doubly Cabibbo suppressed channels.

\( D^0 - \bar{D}^0 \) mixing is very small in the SM, \( x = \Delta m_D / \Gamma_D < < 10^{-2} \). However, quite a number of extensions of the SM, for instance multi-Higgs or supersymmetric extensions, can lead to \( x \sim 10^{-2} \). In these models it is quite natural that there is (new) CP violation associated with \( \Delta C = 2 \) mixing. It is mostly these expectations [23] from SM extensions that nourish the hope of observable mixing and observable indirect and direct CP violation in proposed high statistics charm experiments [19] with \( 10^8 \) to \( 10^9 \) events.

2.3 Beauty

High statistics experiments with the aim of measuring CPV rate asymmetries [24] in \( B \) decays will provide, in a few years, the decisive test of the KM mechanism. These asymmetries are characterized by the angles – conventionally called \( \alpha, \beta, \) and \( \gamma \) – of the well-known CKM unitarity triangle.

Several fits [25,26], using input from CPV in \( K \) decays, \( B^0_d - \bar{B}^0_d \) mixing, etc.,
have been performed to constrain these angles. These fits yield in particular
$0.2 \leq \sin(2\beta) \leq 0.9$, supporting the expectation that CP violation outside
the $K$ system will first be observed through an asymmetry between the rates
of $B^0_d$ and $\bar{B}^0_d \to J/\Psi + K_S$. The integrated rate asymmetry, which can
be calculated in a clean way, is proportional to $\sin(2\beta)$.

Similarly the time integrated rate asymmetry of $B^0_d, \bar{B}^0_d \to \pi^+\pi^-$ is related
to $\sin(2\alpha)$. However, apart from the fact hat these modes have very small
branching ratios, there is an uncertainty in the prediction of the CP asym-
metry because of penguin diagrams contributing to the decay amplitudes. In
principle this uncertainty can be eliminated by an isospin analysis [27]. (Recall
that there is no QCD penguin contribution to the $I = 3/2$ component of
the $B_d \to \pi \pi$ amplitude.) The method requires measuring $B^0_d \to \pi^-\pi^-, \pi^0\pi^0$
and the conjugated channels, and $B^\pm \to \pi^\pm\pi^0$. It will be difficult to carry
out.

The CP parameter $\sin(2\gamma)$ is for instance related to the time integrated
asymmetry of the rates $B^0_s, \bar{B}^0_s \to \rho K_S$. However, that is not a clean and
feasible way of extracting $\sin(2\gamma)$: firstly because these modes have very
small branching ratios and secondly because of theoretical complications in
view of penguin contributions. One proposed alternative is as follows [28]:
From the measured decay rates one has to determine the moduli of the decay
amplitudes for $B^+ \to D^0K^+, \bar{D}^0K^+, D_{1,2}K^+$ and for the charge conjugated
channels. ($D_{1,2}$ are the the CP- even and odd eigenstates.) From the two
triangle relations relating the three complex amplitudes for $B^+$ and for $B^-$,
respectively, one can obtain $\sin^2 \gamma$ up to an ambiguity which can in principle
also be resolved.

According to the KM mechanism for the three generation SM $\alpha + \beta +
\gamma = \pi$. A deviation from this relation would provide evidence for new CP-
violating interactions [29]. (If the sum of these angles turns out to be $\pi$, note
that this does not necessarily imply absence of new CPV effects in the $B$
system.) Of course, more specific searches for new CPV in the $B$ system can
be made, for instance by investigating CP observables that are predicted to
be small in the SM, e.g., the asymmetry in the rate for $B^0_s \to J/\Psi + \phi$ and
its conjugated mode.

## 3 Electric Dipole Moments

The searches for permanent electric dipole moments (EDM), for instance of
the neutron or of an atom with non-degenerate ground are known to be a
very sensitive means to trace new CPV interactions. Recall that a non-zero
EDM of a non-degenerate stationary state would signal P and T violation;
that is, CP violation assuming CPT invariance.

A non-zero atomic EDM $d_A$ could be due to a non-zero electron EDM
$d_e$, non-zero nucleon EDMs, P- and T-violating nucleon-nucleon, and/or
electron-nucleon interactions. Schematically,

$$d_A = R_A d_e + C_A^{eN} + C_A^N. \quad (5)$$
It has been shown long ago [30] that paramagnetic atoms can have large enhancement factors $R_A$. More recent atomic physics calculations [31] obtained for instance for Thallium the factor $R_{Tl} \simeq -585$ with an estimated error of about 10%. For Thallium one has to good approximation $d_{Tl} \simeq d_e R_{Tl} + C_{Tl}$. The nuclear contributions can be neglected for the following reasons: The nuclear ground state of $^{205}$Tl has spin 1/2 and therefore cannot have a nuclear quadrupole moment. A potential (small) contribution of a Schiff moment of the Thallium nucleus is irrelevant at the present level of experimental sensitivity. From the experimental upper bound [32] on $d_{Tl}$ and with $R_{Tl}$ the upper bound $|d_e| < 4 \cdot 10^{-27} e\, cm$ was derived [32].

Very precise experimental upper bounds were obtained on the EDMs of certain diamagnetic atoms, in particular for mercury [33]. The mercury EDM, like that of other diamagnetic atoms, is not sensitive to $d_e$ but to the Schiff moment of the $^{199}$Hg nucleus which at the quark-parton level would be due to non-zero (chromo) EDMs of quarks and/or P- and T-violating quark-quark or gluonic effective interactions. As the transition from the level of partons to the level of a nucleus involves large uncertainties the experimental limits on the EDMs of diamagnetic atoms are difficult to interpret in terms of microscopic models of CP violation [34].

Experimental searches for a non-zero EDM of the neutron at Grenoble [35] and at Gatchina [36] have lead to the upper limit $|d_n| < 9 \cdot 10^{-26} e\, cm$.

Theoretical predictions of the EDM of the electron – or of other leptons – usually constitutes a straightforward problem of perturbation theory because models of CPV are weak coupling theories a posteriori. However, a firm numerical prediction within a given extension of the SM would require knowledge of parameters like masses and couplings of new particles, apart from CP phases. The calculation of $d_n$ and of T-violating nucleon-nucleon interactions, etc. involves in addition methodological uncertainties. For a given model of CPV one can usually construct with reasonable precision the relevant effective P- and T-violating low energy Hamiltonian at the quark gluon level which contains (chromo) EDMs of quarks, the $G\tilde{G}$ and $GG\tilde{G}$ terms, etc. The transition to the nucleon/nuclear level, that is, the computation of T-violating hadronic matrix elements involves large uncertainties. In computing/estimating the neutron EDM naive dimensional estimates, the quark and the MIT bag model [37], sum rule techniques [38–40], and experimental constraints on the quark contribution to the nucleon spin [41] have been used in particular.

The KM phase induces only tiny CP-violating effects in flavour-diagonal amplitudes. Hence the SM predicts tiny particle EDMs (barring the strong CP problem of QCD; i.e., assuming $\Theta_{QCD} = 0$). A typical estimate [37] for the neutron is $|(d_n)^{KM}| < 10^{-30} e\, cm$. In the SM with massless neutrinos CPV in the lepton sector occurs only as a spill-over from the quark sector: one estimates [42] that $|(d_e)^{KM}| < 10^{-37} e\, cm$.

Quite a number of other CPV interactions are conceivable that lead to neutron and electron EDMs of the same order of magnitude as the present experimental upper bounds. (For reviews, see [37, 42, 43].) Multi Higgs extensions of the SM can contain neutral Higgs particles with indefinite CP
parity. Exchange of these bosons induces quark and lepton EDMs already at one loop. For light quarks and leptons the dominant effect occurs at two loops \[^4\]. In two-Higgs doublet extensions \[^3, 4\] of the SM with maximal CPV in the neutral Higgs sector and a light neutral Higgs particle with mass of order 100 GeV neutron and electron EDMs as large as \(10^{-25} e \text{ cm}\) and a few \(10^{-27} e \text{ cm}\), respectively, can be induced.

In the minimal supersymmetric extension of the SM (MSSM) there are in general, apart from the KM phase, extra CP phases due to complex soft SUSY breaking terms. These phases are not bound to be small a priori. They generate quark and lepton EDMs and chromo EDMS of quarks at one-loop order \[^1\], \[^7\], \[^1\] which can be quite large. (Unless the gaugino, squark or slepton masses are close \[^8\] to 1 TeV which causes, however, other problems.) In particular, the prediction for the electron, which is not clouded by hadronic uncertainties, is \(d_e \simeq 10^{-25} \sin \varphi_e (e \text{ cm})\) for neutralino and \(\tilde{e}\) masses of the order of 100 GeV. That means the leptonic SUSY phase \(\varphi_e\) must be quite small, which seems unnatural in the generic MSSM case. (For constrained versions see for instance \[^4\].)

In supersymmetric grand unified theories the small phase problem eases by construction. In the SO(10) model considered in refs. \[^50, 51\] the phases in the soft terms are assumed to be zero at the Planck scale. Unification of the quarks and leptons of a generation into a single multiplet leads, apart from the KM phase, to extra CKM phases entering the fermion-sfermion gaugino (higgsino) interactions at the weak scale. GIM cancellations lead to a smaller \(d_n\) and \(d_e\) than in the generic MSSM – but \(d_e\) can be close to its experimental upper bound.

Clearly, the present experimental EDM bounds have an impact on the parameter spaces of popular extensions of the SM. In particular the bound on \(d_e\) is important in view of the “theoretically clean” predictions. Further improvement of experimental sensitivity is highly desirable. As to future low-energy T violation experiments: A number of proposals \[^52, 53\] have been made to improve the experimental sensitivity to \(d_e\) and to the EDMs of certain atoms by factors of 10 to 100. There is also a new idea \[^54\] to measure the neutron EDM with substantially improved sensitivity.

The present experimental sensitivity to EDMs of quarks and leptons from the second and third fermion generation is typically of the order \(10^{-16}\) to \(10^{-18} e \text{ cm}\) (see below). Although this is orders of magnitude larger than the present limit on \(d_e\) it constitutes nevertheless interesting information. Some CP-violating interactions, for instance CPV Higgs boson or leptoquark exchange, lead to EDMs in the heavy flavour sector that are much larger than \(d_e\) or \(d_n\).

\section{4 High Energy Searches}

Many proposals and studies for CP symmetry tests in high energetic \(e^+e^-\), \(p\bar{p}\), and \(pp\) collisions have been made (see, for instance \[^23, 27, 30, 31\] for some early studies). In particular the production and decay of \(\tau\) leptons, \(b\), and
Quarks are suitable for this purpose, as it allows for searches of new CPV interactions that become stronger in the heavy flavour sector. Contributions from the KM phase to the phenomena discussed below are negligibly small. Typically one pursues statistical tests with suitable asymmetries or correlations. One considers, for some reaction, observables $O_{CP}$ which change sign under a CP transformation. If the scattering amplitude of the reaction is affected by CPV interactions in a significant way then the interference of the CP-invariant and the CPV part of the amplitude generates non-zero expectation values $< O_{CP} >$. Because an unpolarized $f \bar{f}$ state is a CP eigenstate in its c.m. frame it can be shown that unpolarized (and transversely polarized) $e^+e^-$ and $p \bar{p}$ collisions allow for “theoreticaly clean” CP symmetry tests: in these cases $< O_{CP} >$ cannot be faked by CP-invariant interactions as long as the phase space cuts are CP-blind. In the case of $pp$ collisions potential contributions from CP-invariant interactions to an observable being used for a CP symmetry test (e.g., contributions from QCD absorptive parts to T-odd quantities) must be carefully discussed.

In order to maximize the sensitivity to CPV couplings it is often useful to consider so-called optimal observables that maximize the signal-to-noise ratio. For a given reaction and a given model of CPV – or a model independent description of CPV using effective Lagrangians or form factors – with only one or a few small parameters these observables can be constructed in a straightforward fashion.

### 4.1 $e^+e^- \rightarrow \tau^+\tau^-$

CPV effects in tau lepton production with $e^+e^-$ collisions and in $\tau$ decay were discussed in [60–69]. CPV in $e^+e^- \rightarrow \tau^+\tau^-$ can be traced back to non-zero EDM and weak dipole moment (WDM) form factors $d_1^Z(s)$ and $d_2^Z(s)$, respectively, where $s = E^2_{\text{c.m.}}$. These form factors induce a number of CP-odd tau polarization asymmetries and spin-spin correlations, for instance a non-zero $d_2^Z(s)$ (more precisely, the real part of that form factor) leads to a difference in the polarizations of $\tau^+$ and $\tau^-$ orthogonal to the scattering plane. Because the taus auto-analyse their spins through their parity-violating weak decays the tau polarization asymmetries and spin-spin correlations transcribe to a number of CP-odd angular correlations $< O_{CP} >$ among the final states from $\tau^+\tau^-$ decay.

In their pioneering work the OPAL and ALEPH collaborations [70–73] at LEP have demonstrated that CP tests in high energy $e^+e^-$ collisions can be performed with an accuracy at the few per mill level. In the meantime the four LEP experiments measured a number of CP-odd correlations in $e^+e^- \rightarrow \tau^+\tau^-$. They turned out to be consistent with zero. From these results upper limits on the real and imaginary parts of the WDM form factors were derived. The combined upper limit on the real part is $|Re d_2^Z(s = m_Z^2)| < 3.6 \cdot 10^{-18}$ cm (95% CL).

As already mentioned above the tau EDM and WDM form factors can be much larger than the electron EDM. There are a number of SM extensions where the dominant contributions to these form factors are one-loop effects,
being not suppressed by small fermion masses. In these models one has $d_\tau = e \delta/m_Z$ with $\delta$ of order $\alpha/\pi$. For multi Higgs models one finds that $d_\tau$ can reach $10^{-20}e\;cm$, whereas CPV scalar leptoquark exchange can lead to $d_\tau$ as large as $3 \cdot 10^{-19}e\;cm$.

4.2 $e^+e^- \rightarrow b\bar{b}\;\text{gluon}(s)$

CP violation in this neutral current reaction would signal new interactions. At the parton level these interactions would affect correlations among parton momenta/energies and parton spins. While the partonic momentum directions can be reconstructed from the jet directions of flight the spin-polarization of the $b$ quark cannot, in general, be determined with reliable precision due to fragmentation. This implies that useful CP observables are primarily those which originate from partonic momentum correlations. With these correlations only chirality-conserving effective couplings can be probed with reasonable sensitivity. Several correlations were proposed and studied. This situation is in contrast to $\tau^+\tau^-$ and $t\bar{t}$ production (see below) where the fermion polarizations can be traced in the decays. That is why in these cases searches for CPV dipole form factors, which are chirality-flipping, can be made with good precision.

In the framework of SU(2)$_L$-invariant effective Lagrangians it can be shown that chiral invariant CPV effective $ZbbG$ interactions of dimension $d = 6$ (after spontaneous symmetry breaking) exist. In multi Higgs extensions of the SM these interactions can be induced to one-loop order. They remain non-zero in the limit of vanishing $b$ quark mass. Note that these CPV effective interactions are chiral-invariant and flavour-diagonal which is a remarkable feature. A dimensionless coupling $\hat{h}_b$ associated with these interactions turns out to be of the order of a typical one-loop radiative correction, i.e., a few percent if CP phases are maximal. This coupling could be larger in models with excited quarks.

At the $Z$ resonance the above reaction provides an excellent possibility to probe for this type of interactions. The ALEPH collaboration has recently made a CP study with their sample of $Z \rightarrow b\bar{b}G$ events. They obtained a limit of $|\hat{h}_b| < 0.59$ at 95% CL.

4.3 Top Quarks and Higgs Bosons

Because of their extremely short lifetime top quarks decay on average before they can hadronize. This means that the spin properties of $t$ quarks can be inferred with good accuracy from their weak decays, i.e., $t \rightarrow Wb$ in the SM. Like in the case of the tau lepton a number of $t$ spin-polarization and spin-spin correlation effects may be used to search for non-SM physics. Because of their heavy mass top quarks, once they are available in sufficiently large numbers, will be a good probe of the electroweak symmetry breaking sector through their Yukawa couplings. In particular they will be a good probe of Higgs sector CP violation. Many CP tests involving top quarks have been proposed. These proposals include $t\bar{t}$ production in high
energy $e^+e^-$ collisions and in $p\bar{p}$ and $pp$ collisions at Tevatron and LHC energies, respectively. (As already mentioned, in the latter case no genuine CP tests in the way described above can be made. One must carefully discuss and compute potential fake effects.) Useful channels for these tests are the final states from semileptonic decay of both $t$ and $\bar{t}$ and those from semileptonic (nonleptonic) $t(\bar{t})$ decay plus the charge conjugated channels. (The charged lepton from semileptonic $t$ decay is known to be the most efficient $t$ spin analyzer. Nonleptonic $t$ decays, on the other hand, allow for reconstruction of the top momentum.) Observables $O_{CP}$ include triple correlations, energy asymmetries, etc. and their optimized versions. Computations of $< O_{CP} >$ have been made in a model-independent way using effective Lagrangians, form factor parameterizations of the $t$ production and decay vertices, and within several extensions of the SM, notably two-Higgs doublet and supersymmetric extensions. At the upgraded Tevatron one can reach an interesting sensitivity to the chromo EDM form factor of the top of about $\delta d_{chromo} \simeq 10^{-18} e \text{cm}$. Multi Higgs extensions of the SM can induce top EDM, WDM, and chromo EDM form factors of this order of magnitude. EDM and WDM form factors could be searched for most efficiently in $e^+e^- \rightarrow t\bar{t}$ not far above threshold. It was shown that two-Higgs extensions of the SM induce CP effects at the percent level in this reaction.

A possibility to check for CPV Yukawa couplings of the $t$ quark would be associated $t\bar{t}$ Higgs boson production. CP effects can be large but the cross sections are quite small.

If neutral Higgs boson(s) $\varphi$ will be discovered and at least one of them can be produced in reasonably large numbers then the CP properties of the scalar sector could be determined directly by checking whether $\varphi$ has $J^{PC} = 0^{++, 0^{+}, -}$, or whether it has undefined CP parity as predicted by multi Higgs extensions of the SM with Higgs sector CPV. A number of suggestions and theoretical studies in this respect were made. (Some of them follow the textbook descriptions of how to determine the CP parity of $\pi^0$.) In the fermion-antifermion decay of a neutral Higgs particle with undefined CP parity CPV occurs at tree level and manifests itself in a certain spin-spin correlation which can be as large as 0.5. This correlation could be traced in $\varphi \rightarrow \tau^+\tau^-$ and, for heavy $\varphi$, in $\varphi \rightarrow t\bar{t}$. In the latter case, however, the narrow width approximation for $\varphi$ no longer applies. Interference with the non-resonant background $t\bar{t}$ production diminishes the effect.

A “Compton collider” realized by backscattering laser photons off high energy $e^-$ or $e^+$ beams would be an excellent tool to study Higgs bosons by tuning the beams to resonantly produce $\varphi$. The CP properties of $\varphi$ could be checked by appropriate asymmetries and correlations.

5 Summary

The gauge theory paradigm which describes physics so well up to the highest energy scales presently attainable, and the circumstance that the electroweak
symmetry has to be broken spontaneously allows, if there is physics beyond the Standard Theory, for a number of different types of CP-violating interactions that would manifest themselves in different physical situations. Hence searches for CP violation effects should be made in as many particle reactions as possible. $K$ decays and in the near future also hyperon decays may eventually establish direct CP violation in weak transitions. In order to be able to discriminate better between models improved calculations of hadronic matrix elements are needed. The decisive tests of the KM mechanism will be provided by the $B$ meson factories in a few years. The search for a neutron EDM, atomic EDMs, or other T-violation effects in atoms or molecules remain a unique low energy window to physics beyond the SM. Searches of non-SM CP violation can also be made at present and future high energy colliders. In particular if Higgs sector CPV exists effects of up to a few percent are possible in the top quark system. If Higgs boson(s) will be discovered and are produced in large numbers it is also conceivable to eventually study their CP properties directly. It is certainly an experimental challenge to make CP tests at the (sub) percent level at high energy hadron and future $e^+e^-$ colliders – but it will be worthwhile to try.

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