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Mixing and CP Violation: Status and Prospects

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MIXING AND CP VIOLATION: STATUS AND PROSPECTS

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Brief overview of the present status on mixing and CP violation in kaons and B mesons is given by means of the unitarity triangle. Theoretical predictions on ϵ'/ϵ are confronted with experimental results. The prospects of detecting CP violation at high-energy $p\bar{p}$, pp, e^-e^+ and $\mu^-\mu^+$ colliders are discussed in resonant scatterings involving top quarks and/or heavy scalars. The relevance of the latter for baryogenesis is outlined.

1 Introduction

Understanding the origin of charge-conjugation and parity (CP) violation in the $K^0 - \bar{K}^0$ system must be considered as an important task of modern physics, which may eventually help to address the fundamental question concerning the observed asymmetry between matter and anti-matter, the so-called baryon asymmetry in the Universe (BAU). Much theoretical as well as experimental effort has been put to explore the discrete symmetries of time-reversal (T) invariance, CP conservation, and CPT invariance. Even though T/CP is violated in kaons, CPT is still a good symmetry of our quantum world, which has been tested experimentally to a high degree of accuracy. CPT conservation is a generic feature emanating from a consistent field-theoretical description of our nature.

In this brief review, we present some of the highlights regarding the topics of T, CP and CPT violation as follows. In Sect. 2, classical tests of T invariance and CPT invariance are mentioned, and possibilities of breaking CPT and CP within the context of field theories are discussed. In Sect. 3, results for the Cabbibo-Kobayashi-Maskawa (CKM) mixing angles, represented by the unitarity triangle, are given. More attention is paid to the direct CP-violating parameter ε'/ε in Sect. 4. In Sect. 5, the prospects of observing CP violation in resonant top and/or Higgs scatterings at $p\bar{p}$, pp, e^+e^- and $\mu^+\mu^-$ colliders are analyzed. In addition, the significance of this kind of CP-violating phenomena for the BAU is briefly described. Sect. 6 summarizes our current understanding

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of CP violation and mixing and discusses the prospects for the future.

2 Discrete symmetries: T, CP, and CPT

In this section, we shall discuss some classical tests of discrete symmetries. T violation in kaons may be studied via the Kabir's observable [1]

$$A_l(t) \;=\; \frac{|\langle \bar{K}^0(t)|K^0(0)\rangle|^2 \,-\, |\langle K^0(t)|\bar{K}^0(0)\rangle|^2}{|\langle \bar{K}^0(t)|K^0(0)\rangle|^2 \,+\, |\langle K^0(t)|\bar{K}^0(0)\rangle|^2} \;=\; 4\Re e\varepsilon_K\,, \qquad (1)$$

where ε_K is that parameter known from the $K^0 - \bar{K}^0$ mixing. Given the fact that the rule $\Delta S = \Delta Q$ holds phenomenologically, $A_l(t)$ is practically measured at CPLear by comparing the decay chain, $p\bar{p} \to K^+\pi^-\bar{K}^0$; $\bar{K}^0 \to K^0 \to \pi^- e^+ \nu_e$, to that of the decay sequence, $p\bar{p} \to K^-\pi^+K^0$; $K^0 \to \bar{K}^0 \to \pi^+ e^- \bar{\nu}_e$. As a result, at large times ($t \to$ "∞"), $A_l(t)$ modifies to [2]

$$a_l(\text{“}\infty\text{”}) \;=\; 4\Re e\varepsilon_K \;-\; 2\Re e y_l\,, \qquad (2)$$

where $\Re e y_l$ is a CPT-violating term, which was found to be unobservably small at CPLear. Two remarks regarding $A_l(t)$ are now in order. First, a non-vanishing value of $A_l(t)$ would signify T and CP violation independently, without having to resort to the CPT theorem. In the Weisskopf–Wigner (WW) approximation, $A_l(t)$ turns out to be a constant of time. Even though this is a limitation of the WW approach as was already noticed by Khalfin,[3] the deviation from constancy is mainly present at very short (the quantum Zeno region) or very long (power law regime) times. These phenomena have been estimated to be very far beyond the experimental feasibility.[3] Their origin may be traced to the unitarity of the quantum nature.[1]

It is now interesting to discuss various alternatives of how to break CPT and what kind of experimental tests can be carried out to probe CPT invariance. There are few ways to break CPT:

- An obvious attempt would be to provide different masses for particles and anti-particles; this implies a non-Hermitean Hamiltonian. Anti-gravity models,[4] which predict that anti-particles should experience a very small repulsive force within gravitational fields, rely effectively on this option. Since such theories violate the equivalence principle of Einstein, a consistency check for a weaker version of it has been suggested at CPLear.[5]

- Another option may be based on Hawking's observation on the spectrum of radiation of black holes.[6] Hawking has demonstrated that a generalized description of quantum mechanics including gravity allows the evolution of pure states into mixed ones, thus leading to a dynamics that violates conventional quantum mechanics and so breaks CPT. This idea has been applied to $K^0 - \bar{K}^0$ system by the authors in Ref.[7]

- The authors of Ref.[8] formulated an infinite component field theory which effectively steps outside the standard assumption that field theories have to be local. Experiments probing locality with kaons at DAΦNE have already been proposed.[9]

Note that no known example of a theory exists as yet, in which CPT is broken spontaneously. The most crucial experiments testing the validity of CPT with high precision are those involving kaons. More explicitly, one has that

- $M_{K^0} = M_{\bar{K}^0}$. Experiments give the upper bounds on $M_{K^0} - M_{\bar{K}^0}/M_{K^0}$: 3.5×10^{-18} (NA31),[10] 1.3×10^{-18} (E773)[11] and 1.8×10^{-18} (CPLear).[12]

- $\Delta\varphi = \varphi_{00} - \varphi_{+-} = 0$, where φ_{00} and φ_{+-} are the phases of the known amplitude ratios η_{00} and η_{+-}, respectively. On the experimental side, we have $\Delta\varphi^{exp} = 0.2^\circ \pm 2.6^\circ \pm 1.2^\circ$ (NA31)[10] and $0.62^\circ \pm 0.71^\circ \pm 0.75^\circ$ (E773).[11]

- the theoretical value of the superweak phase $\varphi_{sw} = \arctan(-2\Delta M_K/\Gamma)$ $= 43.37^\circ \pm 0.17^\circ$, if one assumes that CP violation originates mainly from $K \longrightarrow \pi\pi$, and one can hence make explicit use of the Bell-Steinberger relation. Experiments are consistent with this result so far.

Even though breaking of CPT may thwart basic field-theoretical requirements, local gauge field theories admit CP violation in general. There are mainly two avenues that achieve that purpose:

- CP violation is explicitly broken by introducing arbitrary complex phases in the Yukawa couplings. For example, the CKM matrix of the SM owes his origin to this mechanism.

- CP violation is broken spontaneously. In this case, the original Lagrangian preserves CP but not the vacuum state. So, after spontaneous symmetry breaking, CP-violating interactions are induced. This mechanism naturally takes place in multi-Higgs scenarios, such as the two-Higgs doublet model of T.D. Lee or Weinberg's three-Higgs doublet model.

Another interesting possibility that exploits both ideas is based on the fact that the CP invariance of the Higgs sector gets broken radiatively, through the presence of very heavy particles, *e.g.*, through heavy Majorana neutrinos.[13]

3 The unitarity triangle

The most efficient way to encode all the information for the mixing parameters is through the Wolfenstein parametrization of the CKM, *viz.*

$$V_{ij} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}. \tag{3}$$

In Eq. 3, V_{ij} has been expanded up to the third order of the Cabbibo angle $\lambda = |V_{us}| = 0.2205 \pm 0.0018$. In this parametrization, $A = |V_{cb}|/|V_{us}^2| = 0.80 \pm 0.04$, whereas less accurately determined are the parameters ρ and η, which are important to describe CP violation in the SM. The unitarity of the CKM matrix allows one to represent the constraints on the mixing angles graphically, by means of a triangle in the complex plane. Among all the six possible unitarity relations, the most useful one is given by

$$V_{ud}^* V_{ub} + V_{cd}^* V_{cb} + V_{td}^* V_{tb} = 0. \tag{4}$$

If we now divide the lhs of Eq. 4 by $V_{cd}^* V_{cb}$, the one side of the triangle will be normalized to unity, while its angles will remain unaffected as is shown in Fig. 1. In the same figure, the various constraints on the combined $\rho - \eta$ values are

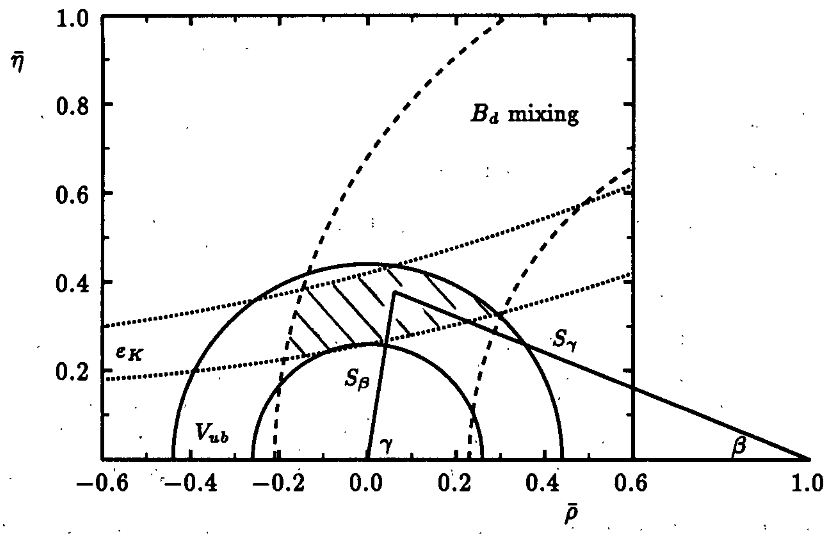

Fig. 1: Constraints on the unitarity triangle ($S_\beta = \frac{V_{ud}^* V_{ub}}{V_{cd}^* V_{cb}}$, $S_\gamma = \frac{V_{td}^* V_{tb}}{V_{cd}^* V_{cb}}$)

implemented. In particular, the length of S_β is confined to lie between the two semicircles determined by $|V_{ub}|/|V_{cb}| = 0.08 \pm 0.03$, coming from semi-leptonic B-meson decays. Similarly, the side S_γ is restricted by two arcs centered at $(\bar{\rho}, \bar{\eta}) = (1, 0)$, which are obtained from B_d-mixing effects. Finally, there are tight constraints originating from indirect CP violation in K^0 mesons.[14–16] From Fig. 1, it is worth noticing that much effort must be put to improve the limits coming from B physics. This also has been the scope of many recent papers.[17]

4 The status of ε'/ε

Of most theoretical as well as phenomenological importance is the question concerning the actual value of the known direct CP-violating parameter ε'/ε. Experimental results and theoretical predictions cannot conclusively exclude any vanishing value for ε'/ε so far. To be specific, the situation is experimentally as follows:

$$\text{NA31:}^{18} \qquad (23.0 \pm 3.6 \pm 5.4) \times 10^{-4}, \tag{5}$$

$$\text{E731:}^{19} \qquad (7.4 \pm 5.2 \pm 2.9) \times 10^{-4}. \tag{6}$$

Even though NA31 appears to rule out the superweak model, which predicts CP violation in $\Delta S = 2$ transitions only, E731 is still consistent with such a realization. On the theoretical side, there have been a number of improvements that have been taken place over the last years,[20] including the top discovery which has enabled more accurate renormalization-group-equation (RGE) studies. There are mainly three groups working on this topic, using different approaches. Their results may be summarized as follows:

$$\text{I:}^{21} \qquad (3.1 \pm 2.5 \pm 0.3) \times 10^{-4}, \tag{7}$$

$$\text{II:}^{22} \qquad (6.7 \pm 2.6) \times 10^{-4} \qquad (m_s = 150 \text{ MeV}), \tag{8}$$

$$\text{III:}^{23} \qquad (9.9 \pm 4.1) \times 10^{-4} \qquad (m_s = 175 \text{ MeV}). \tag{9}$$

The errors in their estimates originate mainly from the different assumptions made for the input data as well as from other uncertainties inherent to the approach used. Yet, much theoretical improvement is needed to come, so as to clarify the possibility of any CP violation beyond the SM.

5 Resonant CP violation and the BAU

It is now important to gauge our chances of finding CP violation at future high-energy scatterings, which can take place at multi-TeV pp or $p\bar{p}$ machines

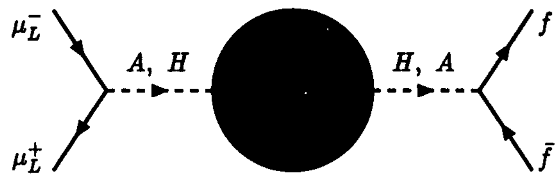

Fig. 2: Resonant CP-violating HA transitions

(*e.g.* LHC or TEVATRON), TeV-e^-e^+ colliders (*e.g.* NLC), or $\mu^+\mu^-$ colliders with variable TeV energy.[24] Particular promising seem to be certain CP-violating observables, which can be resonantly enhanced by particle widths.[25–30]

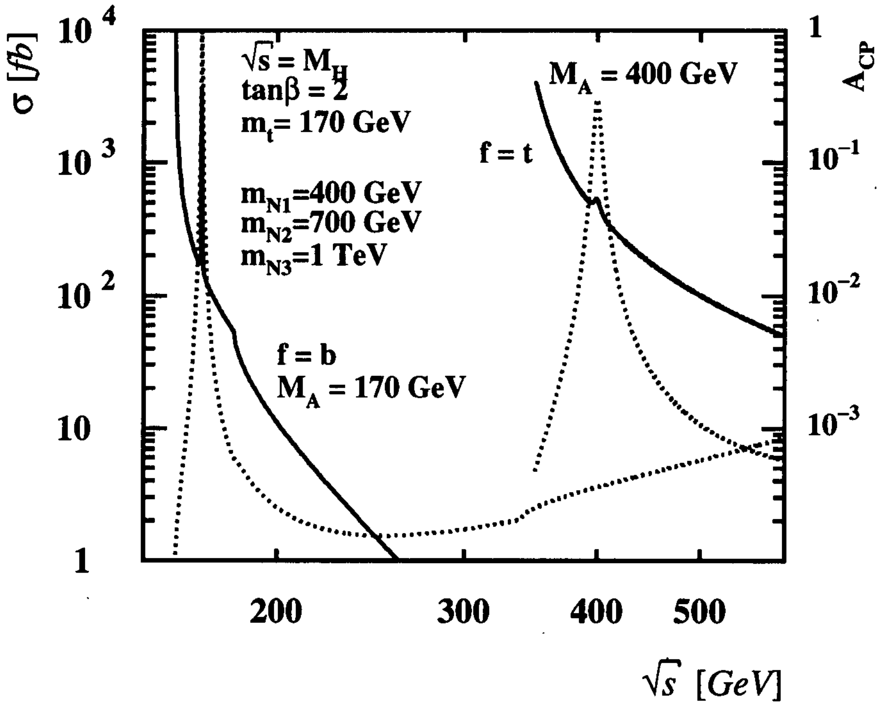

Fig. 3: Production cross-section σ (solid line) and A_{CP} (dashed line)

In simple terms, the focal idea [25] may be explained as follows. At high-energy processes, *e.g.*, $p(W^+)\bar{p}(d) \to (t^*, t'^*, \ldots) \to W^+ b$, heavy particles in intermediate states, such as the t or t' present in models with extra quarks, can resonate, yielding a dynamical phase coming from the Breit-Wigner propagator,

$$\frac{1}{s - m^2 + im\Gamma}. \tag{10}$$

The imaginary CP-even phase, $-im\Gamma$, appearing in the transition amplitude at $s \approx m^2$, will then be multiplied with the CP-odd phases of the theory present in the interaction vertices, so as to produce a real CP-violating contribution to the matrix element squared. Moreover, refinements coming from CPT constraints [28,29] and gauge invariance [31] should be taken into consideration. In this context, another important feature is that specific CP-violating observables based on differential cross sections show a resonant behaviour as a function of s.[26] We will elucidate this point in a $\mu^+\mu^-$ reaction.[30]

Recently, it has been argued [30] that muon colliders is the most ideal place to search for CP-violating resonant transitions of a CP-even Higgs scalar, H, into a CP-odd Higgs scalar, A, as shown in Fig. 2. Assuming that the facility of longitudinal beam polarization is available, one can look for the CP observable

$$A_{CP} \; = \; \frac{\sigma(\mu_L^- \mu_L^+ \to f\bar{f}) - \sigma(\mu_R^- \mu_R^+ \to f\bar{f})}{\sigma(\mu_L^- \mu_L^+ \to f\bar{f}) + \sigma(\mu_R^- \mu_R^+ \to f\bar{f})}. \tag{11}$$

The HA mixing can naturally be induced by heavy Majorana fermions. As such, one may think either of heavy neutralinos and/or charginos in a supersymmetric SM or of heavy Majorana neutrinos present in E_6 motivated models. Adopting the latter realization,[30] we display our numerical estimates of this analysis in Fig. 3. Notice that the mechanism of resonant CP violation is quite important to render A_{CP} measurable.

C and CP violation is also one of the three Sakharov's necessary conditions for generating the BAU, together with B violation and the requirement that the interactions should be out of thermal equilibrium. In general, there are two known scenarios for baryogenesis. In the first scenario, the BAU is generated at the electroweak phase transition,[32] through instanton-type objects (sphalerons) which violate B.[33] In the SM, the so-generated BAU appears to be small.[34,35] However, this is not true in new-physics CP-violating scenarios.[36] In the second scenario, baryogenesis is produced via B-violating decays of heavy particles in the context of grand unified models, such as SO(10). Using the terminology known from kaons, one can differentiate between two mechanisms of CP violation: (i) CP violation present in the decay amplitudes (or ε'-type effects),

(ii) CP violation occuring in the mass matrix (or ε-type effects).[32] The latter may be related to the resonant CP-violating mechanism mentioned above, even though the situation is slightly different in scatterings due to additional interference amplitudes. Finally, one could exploit the fact that sphalerons violate B+L to convert an excess in L into the observed excess in B. This can be achieved by L-violating decays of heavy Majorana neutrinos,[37] which possess both kinds of CP-violating interactions discussed above, *i.e.*, ε and ε'-type.[38]

6 Summary: present and future

In summary, the present status on T/CP/CPT violation may be described as follows:

- Despite the many experimental searches, CPT is still a good symmetry of nature.
- The origin of CP violation is not yet known in the K^0 system. In fact, it must be specified whether CP non-conservation arises due to the CKM matrix or CP is broken spontaneously, or there is another novel origin.
- The knowledge of the top mass and the resulting improved RGE analyses for the $K^0 - \bar{K}^0$ mixing have given rise to more accurate theoretical predictions for ε_K, thus leading to tighter constraints on the $\rho - \eta$ plane.
- The experimental as well as theoretical situation of ε'/ε still remains inconclusive. In particular, we do not know yet whether $\varepsilon'/\varepsilon \neq 0$ or whether CP violation occurs in $\Delta S = 2$ transitions only.

As for the future prospects of testing CP, many options are open. Perhaps, the most appealing ones are given below.

- Many tests of CP violation with B mesons are performed or planned to take place in the so-called B-meson factories, *e.g.*, KEK, SLAC, HERA-B, *etc.* Such tests will probe the sum of all angles in the unitarity triangle with a good precision and may hence consistently check if the CKM-mixing matrix can adequately describe low-energy CP violation.
- Reducing the uncertainties of ε'/ε below the bench-mark of 3. 10^{-4} will be one of the primary aims of future experiments, *e.g.*, DAΦNE.
- At high-energy colliders, there are several CP-violating observables based on the top or Higgs production and decay, which are resonantly enhanced and are very sensitive to new-physics CP-violating scenarios. Detecting

CP-violating phenomena at resonant high-energy scatterings will give another viewpoint of understanding the observed BAU, which also calls for new-physics CP violation.

- There is need for independent tests of T violation, such as looking at possible electric dipole moments for n, e, μ, τ and/or electric dipole form factors of b and t.[39,40]

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