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CP-VIOLATION

A. Pich

Theoretical Physics Division
CERN
CH-1211 Geneva 23

ABSTRACT

The present status of the phenomenology of CP-violation and the prospects for future experimental tests are briefly discussed.

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INTRODUCTION

In the three-generation Standard Model (SM), CP-violation (CPV) originates from the single phase naturally occurring in the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix. The present experimental observations are in agreement with the SM expectations; nevertheless, the correctness of the CKM mechanism is far from being proved. We have no understanding of why nature has chosen the number and properties of fundamental fields just so that CP-violation may be possible. Like fermion masses and quark-mixing angles, the origin of the CKM phase lies in the more obscure part of the SM Lagrangian: the scalar sector. Obviously, CPV could well be a sensitive probe for new physics beyond the SM.

With only two fermion generations, the quark-mixing mechanism cannot give rise to CPV. This implies strong constraints on the SM predictions: for CPV to occur in a particular process, all 3 generations are required to play an active role. In the kaon system, for instance, CPV effects can only appear at the one-loop level, where the top-quark is present. In addition, all CKM-matrix elements must be non-zero and the quarks of a given charge must be non-degenerate in mass. If any of these conditions were not satisfied, the CKM-phase could be rotated away by a redefinition of the quark fields; therefore, CPV effects are necessarily proportional to the product of all CKM-angles, and should vanish in the limit where any two (equal-charge) quark-masses are taken to be equal.

Let the CKM matrix be parametrized in the Maiani-Wolfenstein way:

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4), \quad (1)$$

where $\lambda \simeq \sin\theta_C \simeq 0.22$, $|A| = 0.90 \pm 0.18$ is determined from semileptonic B-decays, and

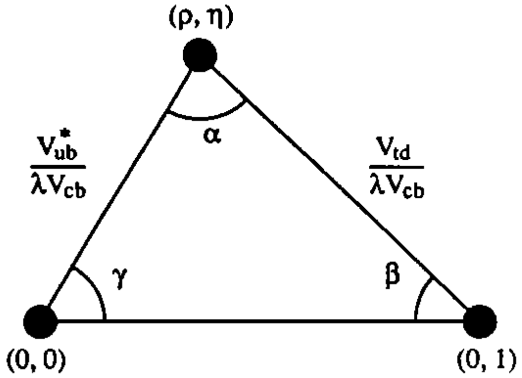

Fig.1. The unitarity triangle serving to define the angles α, β and γ.

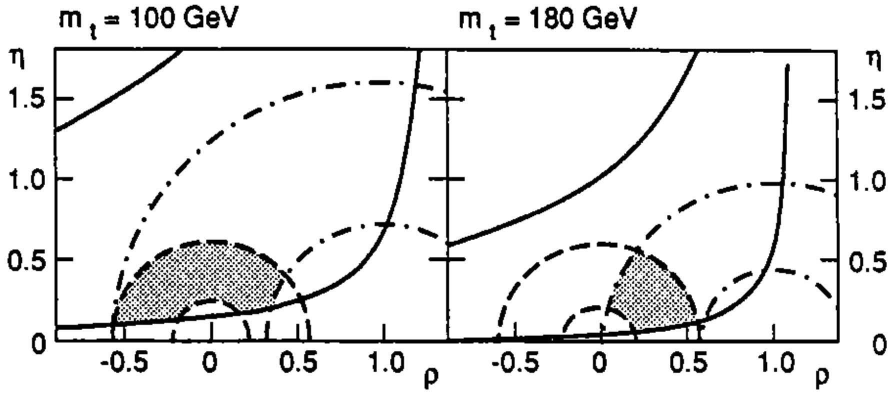

Fig.2. Constraints on the unitarity triangle, for m_t = 100, 180 GeV. The shaded region is allowed.

$\eta \neq 0$ if CP is violated. The unitarity of the 3×3 CKM matrix implies, to leading order in λ, the relation $V_{ub}^* + V_{td} \simeq \lambda V_{cb}$ which can be simply visualized as a triangle in the complex plane. This is shown in fig. 1 where this unitarity triangle has been scaled by dividing its sides by λV_{cb}. In the absence of CPV, this triangle would degenerate into a segment along the real axis.

The present constraints[1] on the unitarity triangle are shown in fig. 2 for two different values of the top-quark mass, m_t = 100 and 180 GeV. Three experimental imputs constrain the position of the ρ, η vertex:

i) The ratio[2] $|V_{ub}/V_{cb}| = 0.09 \pm 0.04$ forces the point (ρ, η) to lie between the two (dashed) circles centred at the origin.

ii) The measured[3] $B^0 - \bar{B}^0$ mixing parameter, $x_d \equiv \Delta M/\Gamma = 0.66 \pm 0.11$, can be translated to information about the CKM-matrix, provided definite values are taken for m_t and $\xi_B \equiv |f_B\sqrt{|B_B|}|$ (which parametrizes the hadronic matrix element of the $\Delta B = 2$ four-quark operator between the B^0 and $\bar{B}^0$ mesons). The actual size of ξ_B has been surrounded by controversy for some time. Since the c and b quarks are quite heavy, many have used the infinite mass limit relation $f_B/f_D \sim \sqrt{m_c/m_b}$ to extrapolate the value of f_D (computed either via QCD-sum rules or lattice simulations) to the bottom-mass scale. Moreover, $B_B = 1$ has usually been assumed. But calculations of the bottom decay constant in the context of QCD-sum rules[4] result in $f_B \geq f_D$, a behaviour recently confirmed by lattice computations[5] . In a direct calculation[6] of the $B^0 - \bar{B}^0$ matrix element (i.e. ξ_B instead of f_B) a large value was also found, the result depending on the input b-quark "pole" mass. Using the presently favoured[4] value $m_b = (4.6 \pm 0.1)$ GeV, one obtains from ref. 6 the range that we shall adopt:

$$\xi_B \equiv |f_B\sqrt{|B_B|}| = (1.7 \pm 0.4) f_\pi, \qquad (2)$$

with which, assuming $B_B = 1$, lattice estimates[5] also agree. Using the experimental input[2] $\tau_b |V_{cb}|^2 = (3.5 \pm 0.6) \times 10^9\ \mathrm{GeV}^{-1}$, the x_d-constraint forces the vertex (ρ, η) to the region between the two (dash-dotted) circles centred at the point (1,0). The bigger circle corresponds to the smaller ξ_B.

iii) The third constraint is imposed by the measured CPV contamination[2] in the $K^0 - \bar{K}^0$ mixing matrix, $|\epsilon| = (2.27 \pm 0.02) \times 10^{-3}$. The main uncertainty here is the size of the hadronic matrix element of the $\Delta S = 2$ four-quark operator between the K^0 and $\bar{K}^0$ mesons, which is usually characterized by the so-called B_K-parameter. Chiral symmetry arguments[7,8,9] and QCD-sum rules calculations[8,10] give B_K-values in the range 1/3 to 1/2. A value around 3/4 is obtained[11] with $1/N_c$ -expansion techniques, and lattice calculations[12] favour $B_K \sim 1$ (the preliminary results[13] of new *improved* lattice simulations seem to prefer, however, smaller values of B_K). We use

$$1/3 \leq B_K \leq 1. \tag{3}$$

The resulting allowed domain for the vertex (ρ, η) of the unitarity triangle is limited by the two hyperbolas (solid curves) in the figures. The smaller values of B_K correspond to bigger values of η.

The intersection of the three regions resulting from the constraints in i), ii) and iii) gives the final allowed domain (shaded area).

$K \to \pi\pi$ DECAYS

The decay $K_L \to \pi\pi$ is an unambiguous sign of CPV. This process can happen either because the K_L has a small admixture of the CP-even state K_1, or because CP is violated in the $K_2 \to \pi\pi$ transition. This is usually parametrized as

$$\eta_{+-} \equiv \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} \approx \varepsilon + \varepsilon' \quad , \quad \eta_{00} \equiv \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} \approx \varepsilon - 2\varepsilon' , \tag{4}$$

where ε characterizes the CPV in the $K^0 - \bar{K}^0$ mixing matrix, and ε' measures the amount of direct CPV in the decay amplitude.

Although the size of ε has been well known for many years, the measurement of a non-zero value for ε' has proved to be difficult. The published results[14] of the two more precise experiments,

$$\mathrm{Re}(\varepsilon'/\varepsilon) = \begin{cases} -(0.4 \pm 1.5) \times 10^{-3} & \mathrm{E731} \\ (3.3 \pm 1.1) \times 10^{-3} & \mathrm{NA31} \end{cases} , \tag{5}$$

are unfortunately not conclusive at present. The E731 result is based upon 20% of its data only; the full data sample is presently being analyzed and a result with better precision is expected soon. On the other side, the NA31 collaboration made additional runs in 1988 and 1989, collecting a total of about three times as much data. A preliminary result of the 1988-data analysis, $\mathrm{Re}(\varepsilon'/\varepsilon) = (1.9 \pm 1.1)10^{-3}$, has been recently reported[15]. This leads to a combined NA31 (1986+1988) result of $(2.7 \pm 0.9) \times 10^{-3}$, giving as new world average

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (1.9 \pm 0.8)10^{-3} \qquad \mathrm{E731} + \mathrm{NA31}\ \text{(preliminary)}. \tag{6}$$

Both groups have presented proposals for improved experiments aiming to reach a precision of about 2×10^{-4}. A similar goal will be attempted at the recently approved Frascati Φ-factory, using the $\Phi \to K_L K_S$ decay as a source of kaons. In the meantime, the LEAR-PS195 experiment is presently running at CERN, trying to reach a more modest 10^{-3} sensitivity, but with a completely different systematics which could nicely complement the E731 and NA31 results.

The CKM mechanism generates CPV effects both in the $\Delta S = 2$ $K^0 - \bar{K}^0$ transition (Box-diagrams) and in the $\Delta S = 1$ decay amplitudes (Penguin diagrams). Although a straightforward and well-defined technique, which makes use of the Operator Product Expansion, is available for a short-distance analysis of these interactions, the final quantitative predictions are obscured by the presence of hadronic matrix-elements of weak four-quark operators, which are governed by long-distance physics. Only one such operator appears in the $K^0 - \bar{K}^0$ calculation; the present uncertainties associated with the size of its hadronic matrix element (the B_K-parameter discussed before) are clearly reflected in the broad allowed region between the two hyperbolas in fig. 2. The theoretical estimate of ε'/ε is much more involved, because many operators need to be considered in the analysis and the presence of cancellations between different contributions tends to amplify the sensitivity to the not very well-controlled long-distance effects. A detailed discussion has been given in ref. 16. For large values of the top-mass, the Z^0-Penguin contributions strongly suppress the expected value of ε'/ε, making the final result very sensitive to m_t. In the presently favoured range of top masses, $m_t \sim 100 - 200\ GeV$, the theoretical estimates give[16] $\varepsilon'/\varepsilon \sim 10^{-3} - 10^{-4}$, with large uncertainties (ε'/ε could even flip sign if $m_t \geq 220 GeV$!). More theoretical work is needed in order to get firm predictions.

RARE K-DECAYS

The decay $K_L \to \pi^0 \nu\bar{\nu}$ is a good example[17] of a (nearly) pure direct CP-violating transition. With an expected branching ratio of about 10^{-11}, the clean observation of just a single *unambiguous* event would indicate the existence of CPV $\Delta S = 1$ transitions. The possibility of detecting such a decay mode is, of course, a big experimental challenge.

The $K_L \to \pi^0 e^+ e^-$ decay looks more promising. If CP were an exact symmetry, only the CP-even state K_1^0 could decay via one-photon emission, while the decay of the CP-odd state K_2^0 would proceed through a two-photon intermediate state and, therefore, its decay amplitude would be suppressed by an additional power of α . When CPV is taken into account, however, an $O(\alpha)$ $K_L \to \pi^0 e^+ e^-$ decay amplitude is induced , both through the small K_1^0 component of the K_L (ε effect) and through direct CPV in the $K_2^0 \to \pi^0 e^+ e^-$ transition. The electromagnetic suppression of the CP-conserving amplitude then makes it plausible that this decay is dominated by the CPV contributions. The branching ratio induced by the direct CPV amplitude is predicted[18] to be around 10^{-11}, the exact number depending on the values of m_t and the quark-mixing angles. The size of the indirect CPV contribution can be calculated using Chiral Perturbation Theory (CHPT) techniques. The prediction[19] has a two-fold ambiguity: the induced branching ratio should be either 1.5×10^{-12} or 1.5×10^{-11}. This ambiguity could be resolved[19] by an experimental study of the e^+e^- invariant mass distribution in the related $K^+ \to \pi^+ e^+ e^-$ process. It is interesting to note that the direct CPV contribution is of the same order as, or even bigger than, the indirect one. This is very different from the situation in $K \to \pi\pi$, where the contribution due to mixing completely dominates. In order to be able to interpret a future experimental measurement of this decay as a CPV signature, it is first necessary, however, to pin down the actual size of the two-photon exchange CP-conserving amplitude. This has been a controversial subject for some time[20]. However, from the recent observation[21] of the $K_L \to \pi^0 \gamma\gamma$ decay-mode, with a $\gamma\gamma$ invariant-mass spectrum peaked at high values as predicted[19] in CHPT, it is possible to conclude that $Br(K_L \to \pi^0 e^+ e^-)_{2\gamma} < 10^{-12}$, implying that this decay is in fact dominated by the CPV contribution[20].

A CPV signal, which is especially sensitive to the presence of light scalars with CPV couplings, is the longitudinal polarization P_L of either muon in the decay $K_L \to \mu^+ \mu^-$. The SM prediction for this observable is expected to be too small to be tested in the near future; nevertheless, it is very important to have a good *quantitative* understanding of its actual size, to allow us to infer, from a measurement of P_L, the existence of a new

CPV-mechanism. A recent analysis[22] has shown, using CHPT methods, that experimental indications for $|P_L| > 5 \times 10^{-3}$ would constitute clear evidence for new physics beyond the SM.

THE NEUTRON ELECTRIC DIPOLE MOMENT

The experimental upper bound on the neutron electric dipole moment[23],

$$d_n^\gamma = (-3 \pm 5) \times 10^{-26}\, e\, cm, \tag{7}$$

provides the more stringent constraint on the so-called θ-vacuum angle, which parametrizes a possible CPV effect in the QCD Lagrangian. The more recent estimate[24], done in the CHPT framework, gives $|\theta| < 5 \times 10^{-10}$.

BEAUTY PHYSICS

Differences of rates that signal CPV are proportional to the small product $A^2\lambda^6\eta$, but the corresponding asymmetries (difference / sum) are enhanced in B-decay relative to K-decay because the B-decay widths involve much smaller CKM elements ($|V_{cb}|^2$ or $|V_{ub}|^2 << |V_{us}|^2$). If the SM is correct, sizeable CPV asymmetries should be expected to show up in many decay modes of beauty particles.

To generate and observable CPV asymmetry in $B^\pm$-decays, one needs two interfering decay amplitudes with different weak (CKM) and strong (final state interactions) phases; the theoretical estimate of these effects is quite uncertain. The situation is much better for those asymmetries[25] involving the decays of B^0 and $\bar{B}^0$ (or B_s^0 and $\bar{B}_s^0$) into a common final state f that is a CP-eigenstate. The B^0 (or $\bar{B}^0$) can decay directly to f, or do so after the meson has been transformed into its antiparticle via the "mixing" process. The interference between these two paths generates a deviation from an exponential decay law in the proper-time evolution of the $B^0 \to f$ ($\bar{B}^0 \to f$) decay rates. If only a single amplitude contributes to the decay process,

$$\Gamma\left[B^0(t)/\bar{B}^0(t) \to f\right] \propto e^{-\Gamma\, t}\{1 \mp \mathrm{Im}(\Lambda)\, \sin(\Delta M\, t)\}, \tag{8}$$

with $\mathrm{Im}(\Lambda)$ a function of the CKM parameters. In some cases, $\mathrm{Im}(\Lambda) \simeq \sin(2\Phi)$, with $\pm\Phi$ one of the angles of the unitarity triangle shown in fig. 1; therefore, it is in principle possible to directly measure these angles and make a test of the unitarity of the CKM matrix. The most realistic channels for the measurement of the angles $\Phi = (\beta, \alpha, \gamma)$ are

$B_d^0 \to J/\psi\, K_S^0$, $B_d^0 \to \pi^+ \pi^-$, $B_s^0 \to \rho^0 K_S$, respectively. The first of these processes is no doubt the one with the cleanest signature and the most tractable background.

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