SLAC-PUB-5000
August 1989
(T/E)

CP VIOLATION IN RARE K DECAYS*

Frederick J. Gilman

Stanford Linear Accelerator Center
Stanford University, Stanford, CA 94309

ABSTRACT

Recent theoretical and experimental progress on CP violation, particularly for rare K decays, is summarized.

Invited talk presented at the Conference on CP Violation in Particle Physics and Astrophysics, Blois, France, May 22-26, 1989.

⋆ Work supported by Department of Energy contract DE-AC03-76SF00515.

Introduction

As is the case for much of contemporary research in high energy physics, the area of CP violation in K decays is to be seen in the context of a much broader effort of looking for physics beyond the Standard Model. There are two principal avenues:

(1) The high energy route involves the direct observation of new quarks, new leptons, heavy Higgs bosons. . . . Of necessity, this involves accelerators which are at the high energy frontier. That frontier, in the past few years, has begun to yield quark-quark (from proton-antiproton colliders) collisions at total energies of order 100 GeV. We now have lepton-lepton (from electron-positron colliders) collisions in this range and quark-quark collisions probing physics up to several hundred GeV. Experiments at the SSC will allow us to explore physics at the 1000 GeV scale and above. This is the natural continuation of the field of high energy physics to higher and higher mass scales.

(2) The "low energy" route also can involve the direct observation of new particles such as additional light neutrinos.. The confirmation of nonzero neutrino mass and mixing would indicate physics beyond the Standard Model as well. However, much of the work at low energy aims to be sensitive to new physics through the indirect, effects of virtual, heavy particles. These, through precision measurements, give us a window on the high energy world which others attack directly.

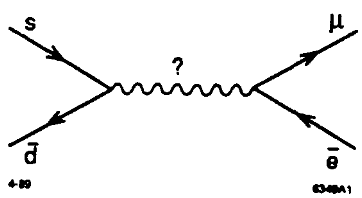

Figure 1: Tree-level diagram involving a flavor-changing gauge boson.

In examining the possibilities for new physics in rare decays, one needs to be acquainted with relatively few generic Feynman diagrams. There are some processes which are forbidden in the Standard Model to any order. An example is leptonic flavor-changing neutral-currents. They might occur at "tree-level," as shown in the diagram in Fig. 1, which could represent the exchange of a flavor-changing "horizontal" gauge boson, for example. There are also processes, which while forbidden at tree-level in the Standard Model, can occur at "one-loop," as indicated by the penguin and box diagrams shown in Fig. 2. Thus, we search for such new physics through:

(*a*) Processes forbidden in the Standard Model, such as would be induced by lepton-flavor-changing neutral currents.

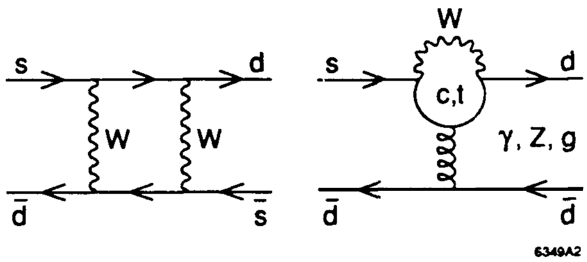

Figure 2: One-loop diagrams giving rise to flavor-changing processes.

(b) Indications that CP-violating phenomena have an origin other than from the non-trivial phase in the quark flavor-mixing matrix of the Standard Model.

(c) Deviations from expected rates, especially for rare processes which are sensitive to heavy virtual particles (from a fourth-generation, super-symmetry, left-right electroweak gauge symmetry, etc.) This is especially true of CP-violating processes, which, in some cases, are especially sensitive to the top quark and possible other high mass particles.

As we pin down and measure the parameters associated with each of the particles in the Standard Model, we use these numbers, together with our improved calculational skills; to obtain updated predictions. Then we can return to the former perspective of looking for new physics by comparing these predictions with all previous data and by pointing to further experiments which are yet more sensitive to new physics.

In this context, we will take a closer look at (b), and particularly at how rare K decays can help determine whether CP violation is a phenomenon whose origin lies inside or outside the Standard Model.

The "Rebirth" of K Physics

The late 1960s and early 1970s marked a peak in experiments on K decays, sparked by the discovery of CP violation.[1)] This effort tailed off as many important measurements were completed and new areas of physics opened up in the 1970s at electron-positron and hadron machines.

Then, in the late 1970s and early 1980s, both theoretical and experimental developments led to a rebirth of K physics. On the theoretical side, the establishment of gauge theories for the strong and electroweak interactions provided a well-defined basis for calculations. The three-generation Standard Model could be used to make predictions of what, by definition, was inside, and by its complement, outside the Standard

Model. The question of "who ordered the muon" was generalized to "who ordered three generations with particular values of masses and mixing angles," and attention was directed at interactions which would connect quarks and leptons of different generations, producing flavor-changing neutral currents. It was realized that not only did the three-generation model provide an origin for CP violation in the nontrivial phase in the quark mixing matrix, but that CP violation should affect the K^0 decay amplitude as well as the $K^0 - \overline{K}^0$ mass matrix, resulting in values of ϵ'/ϵ in the 10^{-3} to 10^{-2} range.[2] There were also predictions for short-distance contributions to a number of other rare K decay amplitudes induced at one-loop, both CP conserving and CP violating.[3]

On the experimental side, great strides were made: to create high flux beams, handle high data rates, incorporate "smart triggers," improve detectors (especially for photons), and to be able to analyze enormous data samples. These matched, at least to some degree, the requirements in precision and rarity being demanded by the theory for incisive tests of the Standard Model. The last few years have seen the beginning of a parade of results which are the culmination of a decade of work in perfecting and performing the needed experiments. Much more is yet to come.

The Rise of the Top Quark

Over the past decade, the "typical" or "best" value of the top quark mass used in theoretical papers has risen monotonically, somehow always remaining one step, or maybe one-and-a-half steps, ahead of the experimental then-current lower bound. Values of 15, 25, 30, 45.. . GeV have been used in various papers (some of them mine), but all of which have fallen by the wayside as experiments have been able to search at higher and higher masses. The present lower limit is around 60 GeV, below which a top quark is said[4] to be "unlikely." It seems that lower limits even higher than this will be quoted at high confidence within a few months, as the analysis of the present round of collider data (which is still being taken as I speak) is completed. An upper limit of around 200 GeV follows from analysis of neutral and charged current data and the measured W and Z masses (i.e., consistency of the ρ parameter with unity).[5] Here again, we will know much more in a few months when we have a much more accurate Z mass from electron-positron colliders. I suspect that we are headed for a lower limit (or a top mass value?!) in the neighborhood of 100 GeV later this year.

The rise of the top quark mass has important consequences when we go to calculate one-loop contributions. For the penguin diagrams in Fig. 2 involving a top and charm quark and a virtual photon (the "electromagnetic penguin"), the conserved nature of the current demands that a factor of q^2, the square of the four-momentum carried by the virtual photon, be present in the numerator of the amplitude. This cancels the $1/q^2$ from the photon propagator; the leading term for small (compared to M_W^2) top mass in the coefficient of the appropriate operator behaves as $\ln(m_t^2/m_c^2)$. By contrast, the "Z penguin" or "W box" involve nonconserved currents: the factor q^2 in the numerator is replaced by the square of the quark mass in the loop and the propagator by $1/(q^2+M_Z^2) \approx 1/M_Z^2$ or $1/M_W^2$. The corresponding coefficient behaves like $[(m_t^2/M_W^2)\ln(m_t^2/M_W^2) - (m_c^2/M_W^2)\ln(m_c^2/M_W^2)]$ when the top mass is small. In days when $m_t^2 \ll M_W^2$, it was completely justified to throw away the Z penguin and W box contributions to such amplitudes in comparison to that of the electromagnetic penguin. Not so any more. The various graphs give comparable contributions, as we will see later in specific examples. Moreover, the contributions from the top quark become the dominant ones to various rare K decays when $m_t^2 >> M_W^2$. In the three-generation Standard Model, as m_t rises farther and farther above M_W, more and more of one-loop K physics is top physics, and we are in the interesting situation where those working at the highest energy hadron colliders are pursuing another aspect of the same physics as those working on the rarest of K decays at low energies.

CP Violation in the Three-Generation Standard Model

The matrix[6] that describes the mixing of three generations of quarks has three real angles and one nontrivial phase. Any difference of rates between a given process and its CP conjugate process (or of a CP-violating amplitude) always has the form:

$$\Gamma - \overline{\Gamma} \propto s_1^2\, s_2\, s_3\, c_1\, c_2\, c_3 \sin\delta_{KM} = s_{12}\, s_{23}\, s_{13}\, c_{12}\, c_{23}\, c_{13}^2 \sin\delta_{13} \quad , \qquad (1)$$

where we express things first in the original parametrization of the quark mixing matrix[6] and then in the "preferred" parametrization adopted by the Particle Data Group,[7] using the shorthand that $s_i = \sin\theta_i$ and $c_i = \cos\theta_i$. Our present experimental knowledge assures us that the approximation of setting the cosines to unity, which we often adopt in the following, induces errors of at most a few percent. In that case, the combination of angle-dependent factors in Eq. (1), involving the invariant measure of CP violation,[8] becomes the approximate combination:

$$s_1^2\ s_2\ s_3\ \sin\delta_{KM} = s_{12}\ s_{23}\ s_{13}\ \sin\delta_{13}\,, \qquad (2)$$

which was recognized earlier as characteristic of CP-violating effects in the three-generation

Standard Model.[9] Equation (1) shows us immediately that all three generations of quarks are necessary for CP violation; in particular, none of the angles can be zero, nor can any of the Kobayashi-Maskawa (K-M) matrix elements.

The K-M factors in Eq. (1) define the "price of CP violation" in the Standard Model. This price must be paid somewhere. It could be paid in a specific process by having many of these factors in both Γ and $\overline{\Gamma}$, corresponding to a very small branching ratio for that process; then, when we form the asymmetry,

$$A_{CP \text{ violation}} = \frac{\Gamma - \overline{\Gamma}}{\Gamma + \overline{\Gamma}} \quad , \tag{3}$$

the smallness of the denominator results in a large asymmetry. On the other hand, the price could be paid by having. few of these factors in Γ and $\overline{\Gamma}$ separately (and hence in their sum), but only in their difference; the asymmetry is correspondingly small. There is, therefore, a very rough correspondence between rarer decays and bigger asymmetries. This rule of thumb is only that; it can be mitigated or exacerbated by other factors: hadronic matrix elements, dependence of one-loop amplitudes upon internal quark masses, and the possible presence of K-M factors in addition to those demanded by Eq. (1). A prime example of luck in this regard is provided by CP-violating effects which depend on $B-\overline{B}$ mixing, where the large top quark mass allows fairly big asymmetries between B and $\overline{B}$ decays to occur in modes which are themselves not suppressed in rate by K-M factors.

Given this price of CP violation, we can "naturally" understand why

$$|\epsilon| \approx 2.28 \times 10^{-3} \tag{4}$$

is so small, i.e., why there is a "near miss," and CP comes so close to being a symmetry in K decays.[10] When all the factors are put in, the size of $|\epsilon|$ is roughly governed by that of $s_2 s_3 s_\delta$. This is naturally of the right size in the technical sense that to have $s_2 s_3 s_\delta$ of order 10^{-3} does not require any angle to be fine-tuned to be either especially small or especially large.

This same factor of $s_2 s_3 s_\delta$ pervades all CP violation observables in the K system, so it is then not so surprising that after 25 years the total evidence for CP violation in Nature consists of a nonzero value of ϵ, and one statistically significant measurement") of a nonzero value of the parameter $\epsilon'/\epsilon = 3.3 \pm 1.1 \times 10^{-3}$, representing CP violation in the $K \to \pi\pi$ decay amplitude itself. Experiments at Fermilab[12] and at CERN[11] are continuing with the aim of reducing the statistical and systematic errors. The value of ϵ' from Ref. 11 is consistent[13-15] with the three-generation Standard Model. Unfortunately, this is not a very strong statement. Other values of ϵ' would be consistent as well because of our lack of knowledge both on the experimental and theoretical fronts:

- The hadronic matrix elements of the penguin operators, upon which the prediction of ϵ' depends, are fairly uncertain. Definitive results will presumably come from lattice QCD calculations which still seem several years away.
- The predictions depend on the value of $s_2 s_3 s_\delta$, which, in turn, depends (aside from another hadronic matrix element) on m_t through imposing the constraint of obtaining the experimental value of ϵ. Very roughly, as m_t goes up, the range allowed for $s_2 s_3 s_\delta$ goes down, and so does the prediction for ϵ'.
- Also as m_t rises, the contributions from Z penguin and W box diagrams begin to be significant. For sufficiently large m_t, a recent calculation[16] contends that most of the usual (strong) penguin contribution to ϵ' can be cancelled in this way.

Experimental and theoretic+ progress over the next few years should clarify these points. But even if the situation becomes that the value of ϵ' is in significant accord with the three-generation Standard Model, this single number is unlikely to be regarded as conclusively establishing that the origin of CP violation lies in the K-M matrix. We would demand additional evidence: A single set of K-M angles (including the phase) must be able to fit several different processes which exhibit CP-violating effects, providing a redundant check on the theory.

Where can we look to get this additional evidence? One place is the B meson system. Here, there isn't a near miss, as CP-violating asymmetries potentially can be very large: of order 10^{-1} or more.[17] Another place is the K system, where we turn to other K decays in which CP-violating effects, although very small, may occur with a different weighting (from that in $K \to \pi\pi$) between effects originating in the mass matrix and in the decay amplitude. Possible K decays which come to mind include $K \to 3\pi$, $K \to \gamma\gamma$, and $K \to \pi\pi\gamma$,[18-20] and especially $K_L \to \pi^0 \ell^+ \ell^-$ and $K_L \to \pi^0 \nu\bar{\nu}$. We follow K decays in the rest of this talk, briefly discussing some rare CP-conserving processes to set the stage for CP-violating decays.

Strangeness-Changing Kaon Amplitudes at One-Loop

$K^0 - \overline{K}^0$ Mixing

The grandfather of all the calculations of amplitudes which are forbidden in lowest order of the electroweak theory is that of the off-diagonal elements of the $K^0 - \overline{K}^0$ mass matrix which generate the $K_L - K_S$ mass difference and ϵ. This still provides the tightest constraint on quark flavor-changing neutral currents (provided, of course, that they contribute to this process). The one-loop, short-distance contribution to ϵ has been already alluded to in our discussion of CP violation.

$K^+ \to \pi^+ \ell^+ \ell^-$ and $K_S \to \pi^0 \ell^+ \ell^-$

Both of these processes receive short-distance contributions from the electromagnetic penguin with a charm quark in the loop. However, there are very large QCD corrections,[21] (so big as to change the sign of the amplitude) and the result is very untrustworthy. Not surprisingly, for the real (CP-conserving) part of the amplitude which enters both these processes, it is necessary to understand significant long-distance contributions. These may be best calculable in chiral perturbation theory.[22]

The measured branching ratio[7] for $K^+ \to \pi^+ e^+ e^-$ is $2.7 \pm 0.5 \times 10^{-7}$. We may expect hundreds, if not thousands, of events from ongoing experiments, as well as some events of $K^+ \to \pi^+ \mu^+ \mu^-$. The predicted branching ratio for $K_S \to \pi^0 \ell^+ \ell^-$ is in the neighborhood of several times 10^{-9}, and will be of importance both for a check on the chiral perturbation theory calculations[22] and for CP violation in the decay $K_L \to \pi^0 \ell^+ \ell^-$, to be discussed later.

$K^+ \to \pi^+ \nu \overline{\nu}$

Here, the short-distance contribution from charm and especially top quarks in Z penguin and W box graphs provides the dominant contribution to the amplitude: all the estimates of long-distance effects show them to be negligible.[23] The QCD corrections are moderate in magnitude. They particularly need to be applied to the contribution of the charm quark. The original QCD corrections,[24] have been recently updated to the case where the top mass is comparable to M_W.[25] The resulting branching ratio for $K^+ \to \pi^+ \nu_e \overline{\nu}_e$ is shown in Fig. 3, with the dashed lines representing upper and lower bounds (given our present freedom in choosing K-M parameters, particularly V_{td}) without QCD corrections and the solid lines giving the corresponding bounds with those corrections.[25] The branching ratio ranges between about 0.2 and 2×10^{-10} per neutrino flavor.

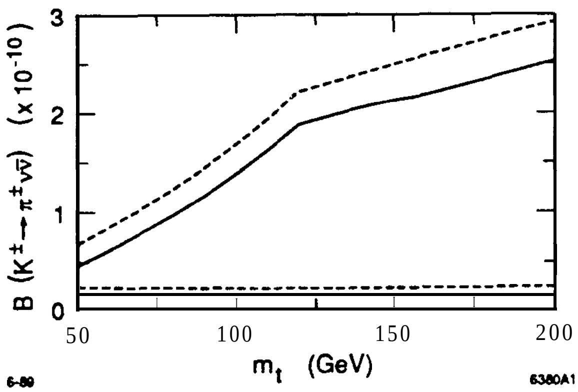

Figure 3: The mazimum and minimum of the branching ratio (per neutrino flavor) for $K^{\pm} \rightarrow \pi^{\pm}\nu\bar{\nu}$ *without (dashed curve) and with (solid curve) QCD corrections* (Λ_{QCD} = 150 *Me V). From Ref. 25.*

The upper limit on this process has recently been considerably improved to 3×10^{-8} by a dedicated Brookhaven experiment.[26] There are prospects of getting to the 10^{-9} level in the next *year,* and eventually reaching a sensitivity where there should be a few events if the Standard Model gives the correct rate. In the meantime, there is a large window still left open for new physics between where we are now and the Standard Model prediction.

$\underline{K_L \rightarrow \pi^0 \ell^+ \ell^-}$

If we define K_1 and K_2 to be the even and odd CP eigenstates, respectively, of the neutral K system, then $K_L \rightarrow \pi^0 e^+ e^-$ has three contributions:

(1) Through a two-photon intermediate state:

$$K_2 \rightarrow \pi^0 \, \gamma\gamma \rightarrow \pi^0 e^+ e^- \quad .$$

This is higher order in α, but is CP conserving. With two real photons, there are two possible Lorentz invariant amplitudes for $K_L \rightarrow \pi^0 \, \gamma\gamma$. One is the coefficient of $F^{(1)}_{\mu\nu} \, F^{(2)}_{\mu\nu}$, which corresponds to the two photons being in a state with total angular momentum zero. Consequently, it picks up a factor of m_e when contracted with the QED amplitude for $\gamma\gamma \rightarrow e^+e^-$, as the interactions are all chirality conserving, and its contribution to the $K_L \rightarrow \pi^0 e^+ e^-$ decay rate is totally negligible.[27] The other invariant amplitude is the coefficient of a tensor which contains two more powers of momentum, and one might hope for its contribution to be suppressed by angular momentum barrier factors. In chiral perturbation theory, an order-of-magnitude estimate[28] for the resulting branching ratio of $K_2 \rightarrow \pi^0 \, e^+ e^-$ is

10^{-14}. However, a vector dominance, pole model predicts[29] a much bigger result: a branching ratio of order 10^{-11}, roughly at the level as that arising from the CP-violating amplitudes (see below). The experimental upper limit on the branching ratio for $K_L \to \pi^0\gamma\gamma$ has very recently been considerably improved,[30] and now is only a few times larger than some of the predictions.[22,29] In the future, we might have not only a measurement of the branching ratio, but also a Dalitz plot distribution which could help distinguish between models. The final answer for this contribution remains to be seen, both theoretically and experimentally.

(2) Through the small (proportional to ϵ) part of the K_L *(i.e.,* K_1), due to CP violation in the mass matrix:

$$K_L \approx K_2 + \epsilon K_1$$
$$K_1 \to \pi^0 \, \gamma_{virtual} \to \pi^0 e^+ e^- \quad .$$

We call this "indirect" CP violation and may calculate its contribution to the decay rate once we know the width for the CP-conserving process $K_1 \to \pi^0 e^+ e^-$. Eventually, there will presumably be an experimental measurement of $\Gamma(K_S \to \pi^0 e^+ e^-)$, which will take all the present theoretical model dependence away. For now, equating this width to the measured one for $K^+ \to \pi^+ e^+ e^-$ gives the estimate:

$$B(K_L \to \pi^0 e^+ e^-)_{\text{indirect}} = 0.58 \times 10^{-11} \quad . \tag{5}$$

(3) Through the large part of the K_L (i.e., K_2), due to CP violation in the decay amplitude:

$$K_2 \to \pi^0 \, \gamma_{virtual} \to \pi^0 e^+ e^- \quad .$$

We call this "direct" CP violation, and the amplitude for it arises from the diagrams shown in Fig. 4. For values of $m_t \ll M_W$, it is the electromagnetic penguin that gives the dominant short-distance contribution to the amplitude, which is summarized in the Wilson coefficient, C_{7V} , of the appropriate operator,

$$Q_{7V} = \alpha \left(\bar{s}\gamma_\mu(1-\gamma_5)d\right)\left(\bar{e}\gamma^\mu e\right) \quad . \tag{6}$$

Values of $m_t \sim M_W$ allow the Z penguin and W box contributions to become comparable to that of the electromagnetic penguin, and bring in another operator,

$$Q_{7A} = \alpha \left(\bar{s}\gamma_\mu(1-\gamma_5)d\right)\left(\bar{e}\gamma^\mu\gamma_5 e\right) \quad . \tag{7}$$

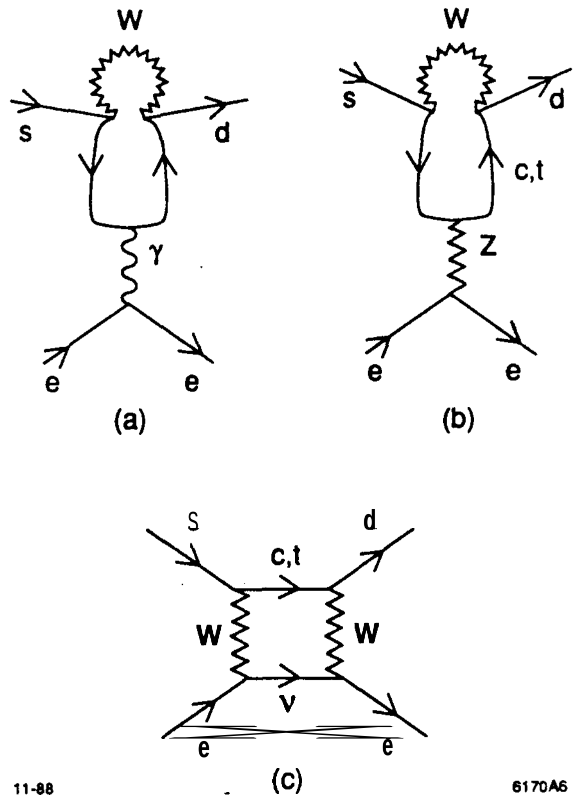

Figure 4: Three diagrams giving a short-distance contribution to the process $K \to \pi\ell^+\ell^-$: (a) the electromagnetic-penguin; (b) the Z penguin; (c) the W box.

The QCD corrections are substantial for the electromagnetic penguin contribution and have been redone for the case[31,32] when $m_t \sim M_W$. In contrast, the top quark contributions from the Z penguin and W box live up at the weak scale and get only small QCD corrections. Still, the coefficient C_{7V} comes largely from the electromagnetic penguin, even after its reduction from QCD corrections. On the other hand, the electromagnetic penguin cannot contribute to C_{7A} , and here it is the Z penguin which gives the dominant contribution. The overall decay rate due to the direct CP-violating amplitude can be obtained by relating the hadronic matrix elements of the operators Q_{7V} and Q_{7A} to that which occurs in K_{e3} decay. Then we find that

$$B(K_L \to \pi^0 e^+ e^-)_{direct} \approx 1 \times 10^{-5} (s_2 s_3 s_\delta)^2 [|\widetilde{C}_7|^2 + |\widetilde{C}_{7A}|^2] . \tag{8}$$

The last factor, shown in Fig. 5, ranges[31] between about 0.1 and 1.0. As $s_2 s_3 s_\delta$ is typically of order 10^{-3}, the corresponding branching ratio induced by this amplitude alone for $K_L \to \pi^0 e^+ e^-$ is around 10^{-11}. Note that when $m_t \gtrsim 150$ GeV, the contribution from C_{7A} overtakes that from C_{7V} , and it is the Z penguin and W box, coming from the top quark with small QCD corrections, which dominate the decay rate.

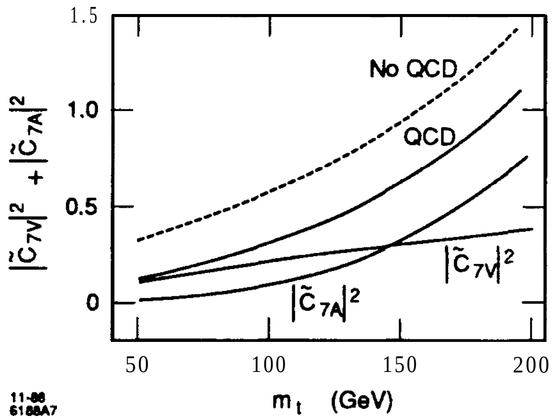

Figure 5: The quantities $(\tilde{C}_{7V})^2$ and $(\tilde{C}_{7A})^2$ as a function of m_t, and their sum, $(\tilde{C}_{7V})^2 + (\tilde{C}_{7A})^2$, with (solid curve, Λ_{QCD} = 150 MeV) and without (dashed curve) QCD corrections, which enter the branching ratio induced for $K_L \to \pi^0\ell^+\ell^-$ by CP violation in the decay amplitude. From Ref. 31.

Thus, it appears at this point that the three contributions from: (1) CP-conserving, (2) indirect CP-violating, and (3) direct CP-violating amplitudes could all be comparable. The weighting of the different pieces in $K_L \to \pi^0 e^+e^-$ is entirely different from that in $K \to \pi\pi$. The present experimental upper limit[33,34] is 4 x 10^{-8}, with prospects of getting to the Standard Model level of around 10^{-11} in the next several years.[35] Hopefully-,-the CP-conserving and indirect CP-violating amplitudes will be pinned down much better by then, permitting an experimental measurement of this decay to be interpreted in terms of the magnitude of the direct CP-violating amplitude.

$K_L \to \pi^0\nu\overline{\nu}$

Having descended to miniscule branching ratios, we now add the impossible in detection: the decay $K_L^0 \to \pi^0\nu_\ell\overline{\nu}_\ell$ is an even more striking example of a process in which the relative sizes of various contributions to the decay rate are totally different[36] than in $K \to \pi\pi$. There is, of course, neither an electromagnetic penguin nor a two-photon, CP-conserving, contribution to the amplitude. Furthermore, the indirect CP violation arising from the neutral K mass matrix gives a negligible contribution to the decay rate. That leaves us with just the Z penguin and W box, and the V-A character of the gauge boson couplings to neutrinos allows only the operator:

$$Q_\nu = \frac{e^2}{4\pi}(\overline{s}_\alpha\gamma_\mu(1-\gamma_5)d_\alpha)(\overline{\nu}_\ell\gamma^\mu(1-\gamma_5)\nu_\ell) \quad . \tag{9}$$

Being CP violating, it is the imaginary part of C_ν that is required:

$$Im\ C_\nu = \left(s_2 s_3 s_\delta\right)\left(\tilde{C}_{\nu,t} - \tilde{C}_{\nu,c}\right) \quad , \tag{10}$$

which is totally dominated by the top quark contribution. The branching ratio (per neutrino flavor) is

$$B(K_L^0 \to \pi^0 \nu_\ell \overline{\nu}_\ell) \approx 2.1 \times 10^{-5} (s_2 s_3 s_\delta)^2 |\widetilde{C}_{\nu,t} - \widetilde{C}_{\nu,c}|^2 \quad , \tag{11}$$

with the latter quantity shown in Fig. 6. Again, as $s_2 s_3 s_\delta$ is of order 10^{-3}, the branching ratio with three generations of neutrinos is of order 10^{-11}. The QCD corrections to the t quark contribution should be small, making this theoretically an ideal decay in which to study CP violation in the decay amplitude. Experimentally, the problems are perhaps best represented by the statement that nobody has yet shown that a measurement of this decay is absolutely impossible.

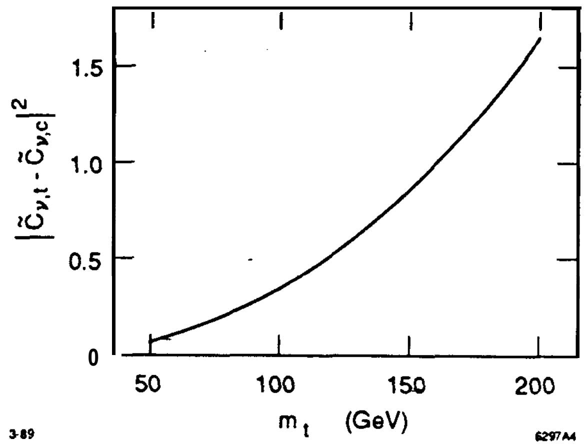

Figure 6: The quantity $|\widetilde{C}_{\nu,t} - \widetilde{C}_{\nu,c}|^2$, which enters the branching ratio for the CP-violating decay $K_L \to \pi^0 \nu_\ell \overline{\nu}_\ell$, as a function of m_t . From Ref. 25.

Conclusion

After 25 years, we are still faced with answering the question of the origin of CP violation: is it a first, tiny bit of physics from beyond the Standard Model, or does it originate from inside the Standard Model, where it is the first evidence that there are three or more generations, all quark masses unequal, and all weak mixing angles nonzero? Indeed, the issue is somewhat more muddled now than it seemed to be a couple of years ago. It has taken longer to gain understanding than we had hoped, but with time, we will sort out the parameters of the Standard Model (including the top quark mass), do the theoretical work that will sharpen the predictions, and carry out the experiments to see CP-violating effects beyond those in the neutral K mass matrix. Nature has been performing an elegant striptease; we just have to be patient and enjoy it.

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