HOW CAN WE FIND OUT WHAT CAUSES CP VIOLATION?*

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INTRODUCTION

Although there have been a number of very fine experiments probing the nature of CP violation, even after 25 years we don't know whether we understand the basic theory involved. We do not know if CP violation is a profound clue to physics beyond the Standard Model and to the origin of the baryon asymmetry, or a trivial accident involving (for example) diagonalizing a mass matrix of quarks or Higgs scalars or neutralinos or squarks. The Standard Model can give a satisfactory description of CP violation in kaon decays to pions without any other contribution, if the phase angle in the CKM matrix is fairly large.

The Standard model description of ϵ and ϵ' depends on some poorly known parameters. Some of those, such as m_t, will be better known soon. Unfortunately, the hadronic matrix elements that enter are not well known, and may not be for a long time. Better measurements of ϵ and ϵ' will provide valuable input to eventually understanding the origin of CP violation, but unless the hadronic matrix elements can be calculated, measurements of ϵ and ϵ' can never give us real confidence that we understand CP violation. In particular, they may never be able to tell us whether a second source of CP violation, about the same size as the Standard Model one, is present.

Most people do not expect the Standard Model to be the sole source of CP violation, for very general reasons. Although the Standard Model describes the world accessible to experiment so far, it leaves unanswered many questions and it is conceptually unsatisfactory. Everyone believes that new physics will appear to help explain why the weak scale is where it is, why there are families, and so on. Every form of new physics that has been thought of so far involves new sets of particles whose interactions will normally have phase factors. That all the new phase angles which enter the more complete theory should be zero would seem to be a miraculous coincidence. These particles could come in the Higgs sector, and/or be supersymmetric partners, and/or leptoquarks, and/or new gauge bosons, or new quarks, or other objects. It cannot be emphasized enough that if the Standard Model were the only origin of CP violation it would be a remarkable fact that would require explanation. Indeed, if the view of a number of people that the excess baryon number of the universe is generated at the weak scale is correct, either new sources of CP violation must exist that are larger than the CP violation in K decay, or that source must have a rapid growth with energy.

Given this situation, it is extremely important to find new ways to get information about the source of CP violation. Even if very accurate experiments

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can be done in the hadronic decay channels of kaons, it is not at all clear that other sources of CP violation as large as the CKM source could be uncovered there. One direction to go is to try to find CP violating effects in other quark decays, and considerable effort is being devoted to learning how to do so for b quarks. Large numbers of b's will be required and facilities that can definitely test Standard Model predictions may be far in the future. Again, it is not certain that hadronic effects in the b system can be eliminated.

Important experiments are underway to measure neutron and electron electric dipole moments (d_n and d_e). It is particularly important to have both, since CP violation can occur in QCD, and a nonzero value for d_n can always be interpreted as due to QCD, whatever the electroweak mechanisms. The Standard Model can only produce d_n and d_e at two loops so it gives predictions orders of magnitude below what could be observed in the foreseeable future. Finding d_n and d_e to be about the same size would imply an electroweak mechanism in addition to the Standard Model one, while finding $|d_n| \gg |d_e|$ would imply that d_n was due to strong interaction CP violation. If d_e is detected in the forseeable future, we immediately know that there is a new source of electroweak CP violation in addition to the CKM phase.

The main point I wish to make in this note is that a number of experiments can be done (eventually) that will tell us (like d_e) immediately whether sources of CP violation exist in addition to the Standard Model one, regardless of interpretation difficulties due to hadronic physics. Let me explain this in the kaon system since that is the most accessible.

CP VIOLATION IN SEMILEPTONIC K DECAYS

The Standard Model predicts no observable CP violation in semileptonic K decays. That is because the decay is a two family one occurring at tree level ($s \to u\mu^-\bar{\nu}$), so the phase in the KM matrix can be put into elements involving the third family, and thus this amplitude is real and CP conserving. $K_{\ell 3}$ and $K_{\ell 4}$ are just different ways of dressing the quarks into hadrons. So the first conclusion[1] is that if a CP violating result is observed in a semileptonic K decay, then the Standard Model can not be the sole source of CP violation. But that prediction is very specific to the Standard Model — in general other possible sources of CP violation do give observable CP violating contributions at tree level to semileptonic K decays, and we have checked[2] that the effects can be large while still consistent with all other constraints.

It turns out that it is possible to do even better. Some specific observables in semileptonic K decays vanish not only in the Standard Model but in larger classes of theories.

The polarization of the muon in $K^+ \to \pi^\circ \mu^+ \nu_\mu$ transverse to the decay plane is a CP violating observable. It is particularly interesting because it vanishes not only for the Standard Model mechanism, but if the effective Lagrangian is a general combination of V, A interactions. Thus a nonzero value for $\langle \vec{s}_\mu \cdot$

$\vec{p}_\pi \times \vec{p}_\mu\rangle$ would demonstrate that there was a non Standard Model source of CP violation and that it gave an effective Lagrangian with S, P interactions. Such S, P interactions could arise from the Higgs sector, from leptoquarks, from supersymmetric partner in loops, and other approaches. Based in part on the arguments I have just summarized, an experiment[3] is underway at KEK to search for the transverse muon polarization.

In $K^+ \to \pi^+\pi^-e^+\nu_e$ one can find terms whose appearance in the angular distribution would violate CP, as noted long ago.[4] A nonzero value for such a term would imply a mechanism for CP violation in addition to the Standard Model one. One such term has a $\sin 2\phi$ angular dependence, where ϕ is the angle between the pion pair plane and the lepton pair plane. That term is particularly interesting because it only gets contributions from V, A effective Lagrangians, not S, P ones. Effects from $\pi\pi$ final state interactions do not prevent the measurement.

One can summarize the approach as in Table 1. Each of several outcomes for several experiments can be explained in a number of ways. No one of them can be definitive. But the pattern from several can tell us how many sources of CP violation there are, and their relative sizes. This approach can be generalized to D and B semileptonic decays in obvious ways, and the W, Z, top, and lepton interactions too, with a larger table. In all of these systems there are observables for which the Standard Model CP violation is unobservably small.

TABLE 1.

Experiment	Mechanism: Standard Model	Strong CP Violation	non-Standard Model V, A effective Lagrangian	non-Standard Model S, P effective Lagrangian
ϵ, ϵ'	yes	no	yes	yes
d_n (at level $\geq 10^{-27} e\ cm$)	no	yes	yes	yes
d_e (at level $\geq 10^{-27} e\ cm$)	no	no	yes	yes
$K_{\mu 3}$ transverse muon polarization	no	no	no	yes
K_{e4} $\sin\phi$ term	no	no	yes	no

This table shows the different ways various mechanisms produce CP violating effects. The entries "yes" and "no" report whether each mechanism is able to produce an observable effect for the experiment in the left-hand column.

My main point in this note has been that learning about the physics of CP violation may require measurements in a number of different processes each with the property that the Standard Model produces negligible CP violation, in order to separate effects. In other processes the Standard Model contribution will occur, but almost certainly so will some other contributions. Art Rich understood this well, and we talked many times on the way to our weekly squash game (or at dinner when our wives got into certain subjects) about whether he could make measurements searching for CP violation in an atomic or nuclear or positronium system (as well as lots of other topics related to particle physics). The problem was that other experiments always indirectly implied that the effects would be too small in the systems he liked. He was less quick to accept the indirect theoretical arguments, but he did. I am grateful that I was Art's friend and I am grateful for the many physics arguments we had. I would like to believe that eventually, as techniques improved, he would have attempted and perhaps succeeded with an experiment about CP violation.

REFERENCES

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