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Topics in CP Violation*

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INTRODUCTION

Given the varied backgrounds of the members of this audience this talk will be a grab bag of topics related to the general theme of CP Violation. I do not have time to dwell in detail on any of them.[1]

First, for the astronomers and astrophysicists among you, I want to begin by reviewing the experimental status of evidence for CP violation in particle processes. There is only one system where this has been observed, and that is in the decays of neutral K mesons.

EXPERIMENTAL CP VIOLATION

The two possible neutral K meson states, with quark content $K^0 = d\bar{s}$ and $\overline{K}^0 = s\bar{d}$, are CP conjugates of each other, that is

$$CP|K^0\rangle = -|\overline{K}^0\rangle \tag{1}$$

Thus the two possible CP eigenstates are

$$|K_{even}\rangle = \frac{|K^0\rangle - |\overline{K}^0\rangle}{\sqrt{2}}, \quad |K_{odd}\rangle = \frac{|K^0\rangle + |\overline{K}^0\rangle}{\sqrt{2}} \tag{2}$$

If CP were an exact symmetry of nature one would expect that these two states would be the mass eigenstates for the neutral kaons, and further that only $|K_{even}\rangle$ could decay to a two pion final state. The odd CP state could decay to three pion final states but not to two pions. Because of the limited phase space available for the three pion decay it would be a significantly longer-lived state. Indeed this explained the experimental results which had earned the kaons the name of strange particles when first discovered. However, as the experiments of Fitch and Cronin[2] convincingly demonstrated in the early

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sixties, the longer-lived neutral kaon state (K_L) decays occasionally to two pions. The observed result is

$$\eta = \left[\frac{\Gamma(K_L \rightarrow \pi\pi)}{\Gamma(K_S \rightarrow \pi\pi)}\right]^{1/2} \approx 2 \times 10^{-3} \tag{3}$$

There are two ways that such a result could arise. One is that the mass eigenstates are mixtures of the two CP eigenstates, that is

$$|K_L\rangle = \frac{|K_{odd}\rangle - \epsilon\,|K_{even}\rangle}{\sqrt{1+\epsilon^2}}. \tag{4}$$

This is referred to as CP violation due to mixing. The second alternative is that there is a directly CP-violating decay

$$|K_{odd}\rangle \rightarrow \pi\pi. \tag{5}$$

This is referred to as direct CP violation and is parameterized by the parameter ϵ' in the following equations.

$$\begin{aligned} \eta^{+-} &= (2.268 \pm 0.023) \times 10^{-3} = \epsilon + \epsilon' \\ \eta^{00} &= (2.253 \pm 0.024) \times 10^{-3} = \epsilon - 2\epsilon' \\ Re(\epsilon'/\epsilon) &= (2.3 \pm 0.7) \times 10^{-3}, \qquad \text{CERN} \\ Re(\epsilon'/\epsilon) &= (0.74 \pm 0.59) \times 10^{-3}, \qquad \text{Fermilab.} \end{aligned} \tag{6}$$

Here the superscripts on η refer to the charges of the two pions. Notice that the contribution for the two channels is equal if ϵ' vanishes. The latest numbers given above, from CERN[3] and Fermilab[4] clearly confirm the Fitch and Cronin result that there is non-vanishing mixing (ϵ) but leave uncertain whether there is in fact a direct decay contribution (ϵ'). Such a contribution is expected in the Standard Model, though there are a number of uncertainties in the prediction of its magnitude.

Decays of the neutral kaons remain the only experimental evidence we have today on CP-violation. The are consistent with the Standard Model, but do not sufficiently test the theory to determine whether the Standard Model mechanism for CP-violation is the only source of these effects or whether there are other contributions.

THEORY—WEAK CP VIOLATION

Let us now step back and ask, in the context of field theories, what properties of the theory give rise to CP violating effects of either type. First a reminder that since all local Lorentz invariant field theories respect CPT the particle physicists tend to assume that CP violation and T violation are the same. Note that CPT ensures that the total decay rate of a particle and its antiparticle are equal. CP violation shows up as differences in partial decay rates for particular channels. How can CP-violating terms can arise in field theories? They occur whenever the Lagrangian includes a coupling constant, or other such parameter, that retains a complex phase after all possible field redefinitions that could remove such phases have been made. It is interesting to note that, in the Standard Model, if there were only two generations of quarks and a single Higgs multiplet, no such phase would be possible; such a theory is automatically CP-conserving. In a three-generation Standard Model with a single Higgs doublet only one such phase remains. It appears in the matrix known as the Cabbibo-Kobayashi-Maskawa or CKM matrix,[5] which is the matrix of quark weak couplings expressed in a basis of quark mass eigenstates. Because only one such phase occurs there are relations between the predictions for a variety of different CP-violating processes in this theory. Extensions of the Standard Model, such as additional Higgs multiplets, or supersymmetry, or technicolor theories, generally add the possibility of additional CP-violating contributions which can destroy those relationships. This makes the measurement of further CP-violating processes, for example in B-decays, an interesting laboratory in which to search for evidence of beyond-Standard-Model effects. I will return to this point later in my talk.

STRONG CP VIOLATION

In addition to the CKM- matrix phase which contribute to weak CP-violating effects there is another very interesting source of CP violation in the Standard Model. This is the term $\theta\epsilon_{\alpha\beta\gamma\delta}F^{\alpha\beta}F^{\gamma\delta}$ that defines the transformation properties of the states under certain non-trivial QCD gauge transformations. (Here F is the non-abelian field strength tensor and I have suppressed the contracted color indices of the two Fs.) The recognition that such a term must be included in the effective Lagrangian for QCD raised a remarkable problem. Since this is a CP-violating contribution to the strong interactions it must be very small indeed for the theory to be consistent with observations. In particular measurements of the neutron electric- dipole moment require[6]

$$\overline{\theta} = \theta + \text{arg. det.} M \leq 10^{-9} \tag{7}$$

Here M is the quark mass matrix. The phase of this matrix can be redefined by quark field redefinitions but this also changes the value of θ. The physically meaningful quantity $\overline{\theta}$ is left unchanged by such redefinitions. The big question is then why is $\overline{\theta}$ so small?

For my taste, only one good answer to that question has been proposed and that is to require an additional global U(1) symmetry, sometimes called Peccei-Quinn symmetry[7], in the Lagrangian.This symmetry, which is non-perturbatively broken by instanton effects, guarantees that the minimum of the effective potential for the Higgs field generates quark masses such that $\bar{\theta} = 0$. This value will be corrected by perturbative corrections but these corrections are small enough to leave Eq. (7) satisfied. It may be interesting for this audience to know that the way that I first thought about this symmetry was to ask a cosmological question. At sufficiently high temperatures in the early universe the quark masses are all zero and hence quark field redefinitions can be used to set $\bar{\theta}$ to zero in this epoch. What can guarantee that when quark masses appear through the Higgs mechanism they do so in a way that maintains this condition? How can one arrange the potential so this is a natural result? The answer is the additional U(1) symmetry. As pointed out by Weinberg[8] and Wilczek[9] a further consequence of this slightly broken symmetry is the existence of a pseudo-goldstone boson, the axion, a particle with interesting astrophysical implications, and a possible dark matter candidate.

In the interests of fairness I must also mention a second possible answer to the strong CP problem, which I call imposed strong CP conservation. One simply requires that $\bar{\theta} = 0$ at a large scale and further that all weak CP-violation comes from either soft or spontaneous breaking terms.[10] This then can achieve the required small value of $\bar{\theta}$ at low energies after perturbative corrections have been included. I find this a rather artificial solution of the problem, since if there are *any* CP-violating terms in the Lagrangian then it seems to me that imposing $\theta = 0$ at any scale has no symmetry justification.

The reason that I raise all this here is that there is some interesting recent work which raises a question about the effectiveness of the Peccei-Quinn mechanism. Holman et al.[11] and independently by Kamionkowski and March-Russell[12] have pointed out that physics such as wormhole effects or any other Plank scale (quantum gravity) physics can be expected to induce higher dimension operators which correct the Lagrangian. Such operators are suppressed by powers of the Plank mass and hence their effects are in general negligible. However these operators typically do not respect the global symmetries of the theory, though they do respect local symmetries. Hence the one situation where such terms may not be negligible is where there is a global symmetry in the Lagrangian which is not respected by the new operators. The possible effect of such operators on the value of $\bar{\theta}$ is large enough to violate (7) in the Peccei-Quinn-type theories. In the theories which do not involve such a symmetry, such as those with imposed strong CP conservation, the effect is indeed negligible. There is a possible escape for the Peccei-Quinn-type theories, and that is to introduce further local symmetries that mix with the $U(1)_{PQ}$ and can effectively protect it from large corrections of this type. The question that merits further exploration is first whether these higher-dimension operators indeed must always occur unless forbidden by such a local symmetry, and if so then whether one can construct satisfactory models of this type that satisfy all the various experimental constraints on the axion.

The axion is being hemmed in on all sides, first by constraints on its parameters from astrophysical phenomena such as energy transport in red giant stars and supernovae, as well as the cosmological constraint that the dark matter axion density must not overclose the universe. Now this new criticism must be considered seriously. I, for one, do not understand quantum gravitational effects well enough to judge this situation. The arguments appear to me to be quite general and therefore a challenge. (However I want to stress, that I am not, as suggested by Frank Wilczek in a later talk, conducting an "onslaught" against the axion, but rather pointing out some questions that have been raised and that require further consideration.)

BARYOGENESIS

So far I have talked about two particle physics topics in CP-violation, though the latter one certainly has some interesting astrophysical connections. Now I want to talk briefly about the major cosmological consequence of CP violation, the generation of the baryon number of the universe. This problem was first addressed by Sakharov.[13] He pointed out that baryon number could be generated, starting from an initially symmetric $N_B = 0$ situation, provided that three conditions are met, namely the theory must contain both baryon-number-violating and CP-violating processes and the universe must go through a period when it is out of equilibrium just before the baryon-number-violating processes are frozen out. Since his seminal paper a number of attempts have been made to consider this problem, which is clearly one of the major questions of cosmology. Note that in any theory that does have baryon number violation it is not sufficient to impose $N_B \neq 0$ as a boundary condition because such a system will evolve to $N_B = 0$ by the usual rules of thermal equilibrium. In grand unified theories there are always baryon-number-violating processes, though in some versions $N_B - N_L$, baryon number minus lepton number, is a conserved quantity.

There are two major epochs in the evolution of the universe that have been considered as the possible time of baryon number generation. The first is at the time of the phase transition in which the grand unified theory breaks down to $SU(3) \times SU(2) \times U(1)$ of the Standard Model and the baryon-number violating interactions of the grand unified theory are frozen out. However it has been pointed out that even after this phase transition there are residual baryon-number violating effects that come from instantons and that, absent a symmetry that fixes $N_B - N_L$, these will tend to remove any baryon number generated at that early transition.[14]

Hence one is led to consider the second possibility, baryon number generation at the phase transition in which the electroweak $SU(2) \times U(1)$ is broken to the $U(1)$ of electromagnetism. The calculation is far from straightforward. One has a bubble of true (broken symmetry) vacuum which is expanding. Excess baryon number that is generated outside the bubble must propagate through the bubble wall into the interior where all baryon number violating processes are frozen out. It is the consensus of those who have studied this problem that, despite uncertainties at many stages of the calculation, they can say with some confidence that the CP-violation that is present in the Standard Model is not sufficient to generate the baryon number of the universe in this transition; one needs some additional source of CP violation such as additional Higgs multiplets to do the job.[15]

Clearly there is an evasion of even this conclusion in models with a $B-L$ symmetry, since in such models the instanton effects do not change $N_B - N_L$ and hence the earlier baryon generation is not eliminated by subsequent processes. However it certainly makes an interesting suggestion that searching for beyond-Standard-Model CP-violating effects may well be worth the effort, even as every other experiment continues to give Standard Model results.

TESTING THE STANDARD MODEL IN B PHYSICS

Fortunately nature provides us with an option to do just that. There is a second system that is very like the neutral kaon system discussed earlier, and that is the neutral B mesons. In fact they provide, at least in theory, an even better laboratory for the study of CP violation because of the number of different channels for their decays in which one can search for CP violation. Furthermore the Standard Model makes very clear predictions for the relationships between these measurements, so that evidence for CP violating physics from beyond the Standard Model can could be found by studying these decays.

In the Standard Model, if there only three quark generations , then the three-by-three CKM matrix of quark weak couplings, V_{ij} , must be unitary. This leads to relationships such as

$$V^*_{ub}V_{ud} + V^*_{cb}V_{cd} + V^*_{tb}V_{td} = 0. \tag{8}$$

Further, if there is only a single Higgs multiplet, then the only CP-violating phase in the theory occurs in this matrix. Thus many CP-violating measurements fix quantities that can be calculated from these matrix elements. A relationship such as (8) that expresses the vanishing of the sum of three complex numbers can of course be represented by a closed triangle in the complex plane. This triangle is referred to as the unitarity triangle. The angles of the triangle can in principle all be measured in B decays and provide a test of the Standard Model relationship of Eq. (8).

I do not have time here to present a detailed review of the experimental situation. None of the measurements can be made with existing facilities. Two classes of experiment have been studied, an asymmetric B factory, which is an e^+e^- collider with unequal beam energies, and a dedicated experiment at a hadron collider or using hadron beams on a fixed target. Table 1 briefly summarizes my understanding of the feasibility of these experiments for measuring the three angles of the triangle. Further study is needed before these

quantity	channel	B-factory	hadron facility
$\arg(V_{cb}^* V_{cd} V_{tb} V_{td}^*)$	ψK_s	yes	yes
$\arg(V_{ub}^* V_{ud} V_{tb} V_{td}^*)$	$\pi\pi, \rho\pi$	probably	background problems
$\arg(V_{ub}^* V_{ud} V_{cb} V_{cd}^*)$	$D^0 K_s$	doubtful	doubtful

Table 1. Comparison of electron and hadron facilities for measuring the unitarity triangle angles in B^0 decays.

statements should be considered definitive. Particularly for hadron machines much work is needed to determine the feasibility of such experiments. Simply put, the hadron machines produce many more B mesons than can be achieved at a B factory, but has problems of mass resolution, hadronic backgrounds and of triggering the detector to select and record the relevant events; it appears unlikely to me that such experiments will be able to measure more than one of the angles of the unitarity triangle. At a B factory two angles can most likely be measured, the third is still questionable. These conclusions depend on as yet unmeasured branching ratios in the decays of neutral B's.

Another way to overconstrain the triangle and hence to test the Standard Model is to measure two angles and two sides. One side, that proportional to $V_{cb}^* V_{cd}$ can be fixed quite well from a combination of measurement and theory[16]. For the second side, proportional to $V_{ub}^* V_{ud}$ the measurement can be made but unfortunately the theoretical calculation that relates that measurement to the parameters is subject to model-dependent corrections that could be quite large.[17]. These corrections need further study.

There are other Standard Model predictions, such as the vanishing of asymmetry in certain channels, that can be tested at a B factory. Further, any observation of CP violation in charged B decays would give evidence for the existence of direct CP violations and hence would also be of great interest even though the Standard Model predictions for these processes have large uncertainties. B physics measurements that can be made at a B factory will increase our understanding of the CKM parameters significantly and possibly offer us a window into the world beyond the Standard Model. I think such a facility offers such exciting prospects for interesting physics that I sincerely hope one will be built somewhere. At present there are several groups, including one at SLAC, one at Cornell, and one KEK in Japan, that are pursuing this idea, but no machine is yet funded. I hope that this situation will change in the next year or so.

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