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CP VIOLATION *

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Abstract

In this talk I briefly review the cosmological importance of CP violation and the status of calculations of baryogenisis in the context of the Standard Model. I then turn to a discussion of Standard Model Predictions for CP violation in B decays, stressing the importance of multiple measurements to overconstrain the model parameters and thus search for indications of beyond-Standard-Model physics.

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INTRODUCTION

Before I begin to discuss CP violation, let me briefly review the framework from which I will speak. I will assume that CPT is a good symmetry. Theorists like symmetries, they simplify our job. We have been forced by experiment to recognize that parity is broken by weak processes, and that CP is also broken, and thus, if we assume CPT is a good symmetry, that T is necessarily also broken. So why do we cling to CPT? The reason is that we do not know how to write any local Lorentz-invariant field theory that does not exhibit CPT symmetry. Even if, as some have speculated, string theories violate CPT, their low-energy realization is as an effective field theory at energies below the Planck scale, and hence such violations must be very suppressed in physics at laboratory energies. Thus, throughout this talk, I will treat CP and T violation as related by the requirement of CPT conservation and CP (rather than C alone) as operation that relates matter to antimatter in our standard theories. Experimental observation of a CPT violation would require major rethinking of our theories of particle physics, rethinking of a much more drastic nature than that required to accommodate the discoveries of P and CP violations.

Why is CP violation important? It must account for a predominant feature of the Universe, the gross imbalance between matter and antimatter. Yet when we look at the basic laws of particle interactions, the Standard Model we find CP violation only in much suppressed terms in the weak interaction decay matrix, terms which manifest themselves as CP violations in K decays at the level of approximately 1 part in 10^{-3} in neutral K decays. Until the discovery of these effects in 1964 [1] particle physicists preferred theories of the fundamental interactions that had exact CP symmetry.

Why did this not seem in blatant contradiction to the observed structure of the Universe? In the context of theories with exact CP symmetry, the matter-antimatter asymmetry of the universe must simply be taken as an initial condition on the evolution of the universe. Today that is still one possible answer. If we choose particle theories with exact baryon number conservation, then the imbalance must have been present from in the very earliest stages of the evolution of the universe. Since baryon number conservation was another symmetry that physicists of that period assumed was exact, this picture contained no contradictions.

However, unwillingness to assign effects to complicated boundary conditions is one of the major differences between physicists and creationists. Whenever possible we would prefer to explain effects as arising from the underlying dynamics of the laws of physics, rather than from delicately chosen initial conditions. In many cases we are even forced to do this. In theories without symmetries such as Baryon number conservation, any influence of initial conditions on net baryon number would be eliminated by the inevitable relaxation to thermal equilibrium, that is to equal populations of each particle and its antiparticle.

Today there is a large class of particle theories that do not have baryon number conservation. Instead they have "Grand Unification" of the electroweak and strong gauge groups into a larger gauge group, in which there are baryon number violating processes. These are extremely suppressed under current conditions, because the mediating particles are very massive. However in the early stages of the universe the temperature is high enough that the grand-unifying symmetry is unbroken and so baryon violating processes occur at rates comparable to all other interactions. In all such theories the early universe develops equal matter and antimatter content, as a consequence of thermal equilibrium alone. Then the current universal imbalance must be explained.

1. A BRIEF OVERVIEW OF IDEAS ON BARYOGENISIS

Baryogenesis is the cosmologist's term for the development of an imbalance between baryons and anti-baryons at some stage in the evolution of the universe. In 1967 Sakharov stated three conditions that are necessary for the development of such an asymmetry [2]:

1. It can only occur at a stage when the Universe is out of thermal equilibrium.

2. There must be baryon number violating processes that are active at that stage, but that are "frozen out" by the time thermal equilibrium is restored.

3. There must be CP violation, otherwise any baryon-producing process is bal-

anced by an equal rate CP-conjugate process that is baryon-destroying, and hence no imbalance can develop.

Let us consider these in reverse order:

• In the Standard Model alone we have CP violation arising from a single phase in the three generation weak decay matrix, known as the Cabibbo-Kobayashi-Maskawa (CKM) matrix. In many beyond-Standard-Model theories there are further sources of CP violation in other couplings.

• Modern particle physics theories for physics beyond the Standard Model almost all include the notion of unification of the $SU(3) \times SU(2) \times U(1)$, gauge groups into a single larger group at some high scale. In such Grand Unified theories there are typically baryon number violating processes mediated by the additional gauge bosons that appear in the larger gauge group.

• In modern theories of cosmology there are a number of out-of-equilibrium stages in the evolution of the universe, generally associated with the occurrence of a transition from one realization of the symmetries of the particle theory to another. Thus in Grand Unified theories there is a scale, generally called the GUT scale at which the symmetry is broken from the gauge group of the grand-unification, down to the Standard Model, $SU(3) \times SU(2) \times U(1)$, and a smaller scale, known as the weak scale at which the electroweak symmetry $SU(2) \times U(1)$ is broken down to the electromagnetic $U(1)$.

Above the GUT scale processes involving the additional gauge bosons of the grand unified theory are unsuppressed. These include baryon number violating processes. Such processes are frozen out below the GUT scale because the additional gauge bosons acquire large masses in that transition. Hence processes that they mediate are suppressed at all lower temperatures. Thus the first place where people looked for the source of baryon-number violation was in this transition.

However it was later realized that there are residual non-perturbative baryon number violating processes that continue to be active at all temperatures down to the weak scale. [3] Thus unless there is a $B - L$ symmetry to protect it, the relaxation to thermal equilibrium would wipe out any baryon number produced at the GUT scale. Then we must look for a way to generate the observed asymmetry at the weak scale transition. I will now concentrate on this latter option since it appears the more interesting from the point of view of studies of CP violation. However it is important to remember that, if we eliminate the possibility that there is sufficient weak-scale baryogenisis to account the for the observed universal baryon excess, then one option is to conclude that we must choose a theory with strong scale baryogenesis and a surviving $B-L$ symmetry to protect the baryon number excess from the relaxation to thermal equilibrium.

In theories with weak scale baryogenisis the Standard Model seems to have a problem. If we assume the Standard Model CKM matrix is the only source of CP violation we do not get a large enough baryon number generated. The number to be calculated is n_B/S, where n_B is the baryon number density and S is the entropy density, which is chiefly due to the 2.7 K background radiation. The observed number is $n_B/S \cong 10^{-10} - 10^{-11}$, calculations from the Standard Model typically produce numbers many orders of magnitude smaller.

The calculations are quite complex and results depend on a number of simplifying assumptions. The general nature of the calculation is shown in a cartoon fashion in Figure 1. The phase transition takes place by the formation of a bubble. The inside of the the bubble is in the low-temperature broken-symmetry phase and all baryon-number violating processes are extremely suppressed, so can be ignored. Outside the bubble non-perturbative baryon-number violating processes are active, so thermal equilibrium guarantees equal populations of matter and antimatter. The critical arena for the generation of the asymmetry is a differential transmission of baryons, as compared to antibaryons, through the wall of the bubble, the out-of-equilibrium region.

Now the region around such a bubble wall is exactly the area about which we know least in such theories. Generally calculations of such a phase transition rely on an approximation that the wall is thin and that the bubble expands rapidly, so that

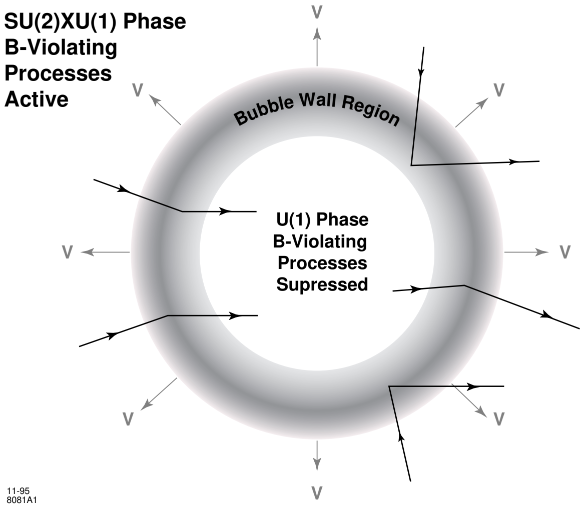

Figure 1: Cartoon of weak scale phase transition.

the wall travels at close to the speed of light. Quite possibly, for the real parameters of the theory, the wall is not very thin, and its velocity may be only a small fraction of the speed of light. These are just two of the points that make it quite difficult to obtain definitive results. Farrar and Shaposnikov [4] argue that it is possible to generate the required asymmetry with the Standard Model CP violation, but their claims have been criticized and the majority opinion appears to be that the Standard Model gives a number more like $n_B/S \leq 10^{-26}$! [5]

The relevance of this result to laboratory studies of CP violation is merely suggestive. If we take it seriously it suggests that the minimal Standard Model CP violation from the CKM matrix is not the full story. It must be augmented with other sources of CP violation to achieve sufficient baryon number asymmetry in any of large class of GUT-type theories that do not have $B-L$ symmetry. This argument, while not compelling, suggests that CP violations in B-decays provide a possible low energy window to beyond-Standard-Model effects.

2.STANDARD MODEL PREDICTIONS FOR CP VIOLATION IN B DECAYS

I now turn to the predictions of CP violating effects in B decays in the context of the Standard Model. The aim of studies of B physics over the next ten years or so will be to test these predictions in as many ways as possible, and thus provide a redundant or over-determined set of measurements of the Standard Model parameters. Any inconsistencies between the various measurements will be suggestions of non-Standard Model effects and will perhaps provide clues which will help us move beyond the current Standard Model in our understanding of fundamental particle processes.

In the Standard Model there is a single CP violating parameter which introduces complex terms in the CKM matrix. The form of this matrix is convention dependent, but its CP violating consequences are not. We will use the standard Particle Data Group convention, which is to define the phase of the element V_{ub} to be the the parameter introducing CP violation while all other elements in the first row and the third column are real. Unitarity then introduces imaginary parts into the remaining CKM elements, but except for V_{td} they are small relative to the corresponding real parts. The CKM matrix can be written

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$\simeq \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$$+O(\lambda^4)\ .$$

where the second expression uses a notation due to Wolfenstein for which $\lambda = sin(\theta_{Cabibbo})$. Terms of order λ^4 and higher have been dropped. In this convention we can read off a phase coming from the CKM matrix for any weak decay amplitude contribution. We call this the weak phase. Decay amplitudes also acquire phases from final state interactions, i.e. rescattering processes due to strong interactions. We call this a strong phase.

Now the crucial element for CP violation is the fact that, when we go to the amplitude for the related CP-conjugate process, the weak phase changes sign but the strong phase does not. If we were dealing with a process with only one term in the amplitude for the decay this phase would not matter, the phases in such a case are completely unphysical. However when interference occurs between two or more contributions to the decay amplitude the phases can play a physical role.

Direct CP violation is the name given to a process where there is a difference in rate between a process and its CP conjugate because there are two different Feynman diagrams with different weak phases which contribute to the decay. Suppose we have

$$\mathcal{A} = \Sigma_i \mathcal{A}_i e^{i(\delta_i+\phi_i)} \ , \ \overline{\mathcal{A}} = \Sigma_i \mathcal{A}_i e^{i(\delta_i-\phi_i)} \ .$$

where δ_i is the strong phase and ϕ_i the weak phase of the i^{th} term and the $\mathcal{A}_i$ are all real—then the asymmetry in rates is given by

$$a = \frac{|\mathcal{A}|^2 - |\overline{\mathcal{A}}|^2}{|\mathcal{A}|^2 + |\overline{\mathcal{A}}|^2}$$

To get a rate asymmetry there must be at least two terms in the sum, furthermore not only must the two amplitudes have different weak phases, they also must have different strong phases. Such effects are expected in the Standard Model in many channels. There are two classes of diagrams, known as tree and penguin (i.e. W-loop) diagrams. Often these both contribute to the same decay process, but with different weak phases. Even when there is no tree contribution, asymmetries can arise from interference between two penguin contributions with different quarks in the loop. All direct CP violation effects vanish if we arbitrarily set the CKM phase parameter to zero, as is done in the "superweak" theories.

It would be very interesting to observe such effects, which are expected in a number of charged B decays channels, and also in some b-baryon decays. However they not very useful for extracting a measurement of the weak phase and other CKM parameters because of their dependence on the difference of the strong phases of the two contributions. Strong phases are notoriously difficult to calculate from first principles. There are indeed models and approximations which allow predictions of these quantities, but a deviation from these predictions would challenge only the model or the assumptions made used for the calculation – not the fundamental parameters of CP violation in the Standard Model.

In the K decay case direct decay contributions are suppressed by a cancellation between contributions from penguin diagrams with gluon emission and those with Z emission from the W-loop (electroweak penguins). The latter are enhanced by the large top quark mass and are competitive in size with the gluon terms. There is no reason to expect a similar cancellation will occur to suppress direct CP violation in B decays, although once again the Z-penguin contributions can be significant and will need to be taken into account in comparison of theory and experiment.

A second class of CP violating effects, familiar from their appearance in the decays of neutral K's, is CP violation in the decay neutral mesons to final states of definite CP. This can be described as due to interference between two paths to the same final state, one a direct decay, the other a mixing to the CP-conjugate meson and then decay. Here the weak phase of the mixing combines with the weak phase of the decay amplitude so even processes with only a single amplitude contribution (or with several that all have the same weak phase) can generate CP violating effects of this type. For such processes there is a very simple relationship between the measurable asymmetry and the CKM matrix element phases, so these are the cases of greatest interest for developing tests of the Standard Model.

In the Standard Model mixing in the $K^0-\overline{K}^0$; $B^0_d-\overline{B}^0_d$; and $B^0_s-\overline{B}^0_s$ systems is large, while that expected for the $D^0-\overline{D}^0$ and $D^0_s-\overline{D}^0_s$ systems is very small. Standard Model predictions for CP violation in D decays are so small that any detected effect would be evidence for beyond-Standard-Model physics. However in the B system mixing is large and the half-life is long compared to the mixing time, so the Standard Model predicts significant asymmetries. Thus B's are an ideal system for the study of CP violation.

I will now summarize the Standard Model predictions for various quark processes and their implications for both B_d and B_s decays, as well as for direct CP violations in two tables. I find these tables are a useful way to organize the information.

Table 1 list quark processes $b \to q\overline{q}'s$. Penguin contributions appear only when $q =$

Table 1: Leading CKM coefficients for Decays $b \to q\overline{q}'s$

Decay	CKM Factors (Order in λ)		B_d Modes (Angle Measured)	B_s Modes (Angle Measured)
	Tree	Dominant Penguin		
$b \to c\overline{c}s$	$V_{cb}V_{cs}^*$ (λ^2)	$V_{cb}V_{cs}^*$ (λ^2)	ψK_S (β)	$\psi\phi$ (0)
$b \to s\overline{s}s$	0	$V_{cb}V_{cs}^*$ (λ^2)	ϕK_S (β)	$\phi\eta'$ (0)
$b \to u\overline{u}s$	$V_{ub}V_{us}^*$ (λ^4)	$V_{cb}V_{cs}^*$ (λ^2)	$\pi^0 K^0$ (Direct CP Violation)	K^+K^-, $K^0\overline{K}^0$ (Direct CP Violation)
$b \to d\overline{d}s$	0			
$b \to c\overline{u}s$	$V_{cb}V_{us}^*$ (λ^3)	0	$D^0 K \to \pi^+\pi^- K$	$D^0\pi^0 \to \pi^+\pi^-\pi^0$
$b \to u\overline{c}s$	$V_{ub}V_{cs}^*$ (λ^3)	0	$\overline{D}^0 K \to \pi^+\pi^- K$ (γ)	$\overline{D}^0\pi^0 \to \pi^+\pi^-\pi^0$

q'. The QCD-penguin contributions have been rewritten using the three generation CKM unitary equation

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

to eliminate the coefficient of the top quark contribution, giving

$$\begin{aligned} A^s_{penguin} &= V_{td}V_{tb}^* f(m_t) + V_{cd}V_{cb}^* f(m_c) \\ &\quad + V_{ud}V_{ub}^* f(m_u) \\ &= V_{cd}V_{cb}^*(f(m_c) - f(m_t)) \\ &\quad + V_{ud}V_{ub}^*(f(m_u) - f(m_t)) \end{aligned}$$

The first term in this rewritten amplitude is of order λ^2 while the second is of order λ^4 and so is negligible compared to the first. Hence in the table we have dropped the second term, and written only the coefficient of the first to define the weak phase of the penguin contributions.

Table 2 lists $b \to q\overline{q}'d$ processes A similar procedure has been used to simplify the penguin terms. Here we choose to eliminate the coefficient $V_{cb}V_{cd}^*$. This leaves two terms with CKM coefficients of comparable size. However the function multiplied by

Table 2: Leading CKM coefficients for Decays $b \to q\overline{q}'d$

Decay	CKM Factors (Order in λ)		B_d Modes (Angle Measured)	B_s Modes (Angle Measured)
	Tree	Dominant Penguin		
$b \to c\overline{c}d$	$V_{cb}V_{cd}^*$ (λ^3)	$V_{tb}V_{td}^*$ (λ^3)	$\psi\pi$, D^+D^- (β)†	ψK_S (Direct CP Violation)
$b \to s\overline{s}d$	0	$V_{tb}V_{td}^*$ (λ^3)	$\phi\pi^0$, $K_S\overline{K}_S$ (Direct CP Violation)	ϕK_S (β)†
$b \to u\overline{u}d$	$V_{ub}V_{ud}^*$ (λ^3)	$V_{tb}V_{td}^*$ (λ^3)	$\pi\pi$, $\rho\pi$, $a_1\pi$ (α)†	ρK_S, $\pi^0 K_S$ (γ)†
$b \to d\overline{d}d$	0			
$b \to c\overline{u}d$	$V_{cb}V_{ud}^*$ (λ^2)	0	$D^0\pi^0 \to \pi^+\pi^-\pi^0$ $\overline{D}^0 K_S \to \pi^+\pi^- K_S$	$D^0 K_S \to \pi^+\pi^- K_S$ $\overline{D}^0 K_S \to \pi^+\pi^- K_S$
$b \to u\overline{c}d$	$V_{ub}V_{cd}^*$ (λ^4)	0	($-$)	($-$)

† Neglecting small direct CP violation effects.

the $V_{ub}V_{ud}^*$ coefficient would vanish if the charm and quark masses were equal and is quite small relative to the other term. Thus in the table we have dropped this term. However it should not be forgotten altogether. In particular, when there are no tree terms, as for example in $b \to s\overline{s}d$, the interference between this term and the dominant penguin term can cause direct CP violation, giving perhaps as much as a 10% asymmetry [7].

These two tables give you a glimpse of the rich array of predicted CP violation effects expected in the decays of B mesons. We will hear tomorrow a number of different proposals on how to measure these effects. These experiments may fit the Standard Model predictions, or, if the hints from the baryogenis problem mean anything, they may not. Either way we will know more than we now do about CP violation.

3. PREDICTIONS OF BEYOND STANDARD MODEL THEORIES

The next question is what different results do we expect in theories beyond the Standard Model? The answer depends on the particular theory. Let me here just comment on the most common modification, which comes from additional CP violation in some non-standard sector of the theory. The most likely way for such an effect to manifest itself in low-energy weak processes is as an additional set of contributions to the mixing between the CP conjugate pairs of particles such as B^0 and $\overline{B}^0$. Since the Standard Model predictions depend on the mixing weak phase as well as on the decay weak phase these predictions can be significantly altered by such a term. How might the results conflict with the Standard Model predictions? For example, in the Standard Model, once having measured any two of the three angles, we can extract a prediction for V_{ub} or V_{td} from the shape of the unitarity triangle. If the mixing angle is different from the Standard Model value, then this prediction will not agree with other measurements of these quantities. Thus it is important not just to extract CP asymmetries, but also to pin down all the remaining CKM parameters as accurately as possible. This will take both theoretical and experimental improvements over current knowledge.

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