CP Violation – A Brief Review

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Abstract. Some past, present, and future aspects of CP violation are reviewed. The discrete symmetries C, P, and T are introduced with an example drawn from Maxwell’s Equations. The history of the discovery of CP violation in the kaon system is described briefly, and brought up-to-date with a review of recent results on kaon decays. The candidate theory of CP violation, based on phases in the Cabibbo-Kobayashi-Maskawa (CKM) matrix, will be tested by studies of B mesons, both in decays to CP eigenstates and in “direct” decays; we will soon learn a great deal more about whether the CKM picture is self-consistent. Future measurements are noted and some brief remarks are made about the “other” manifestation of CP violation, the baryon asymmetry of the Universe.

I INTRODUCTION

Fundamental discrete symmetries have provided both guidance and puzzles in our evolving understanding of elementary particle interactions. The discrete symmetries C (charge inversion), P (parity, or space reflection), and T (time reversal) are preserved by strong and electromagnetic processes, but violated by weak decays. For a brief period of several years, it was thought that the products CP and T were preserved by all processes, but that belief was shattered with the discovery of CP violation in neutral kaon decays in 1964 [1]. The product CPT seems to be preserved, as is expected in local Lorentz-invariant quantum field theories [2].

Since 1973 we have had a candidate theory of CP violation [3], based on phases in the coupling constants describing the weak charge-changing transitions of quarks. These couplings are described by the unitary $3 \times 3$ Cabibbo-Kobayashi-Maskawa (CKM) [3,4] matrix. This theory has survived a qualitative test with the establishment of direct CP violation in neutral kaon decays [5,6]. It is well on its way to being tested in a wealth of $B$ decay processes. Will these tests be passed? What are the implications in either case? What will we learn about the “other” manifes-
TABLE 1. Behavior of Maxwell’s equations under discrete symmetries.

| Equation                                      | P | T | C | CPT |
|-----------------------------------------------|---|---|---|-----|
| $\nabla \cdot E = 4\pi \rho$                  | + | + | - | -   |
| $\nabla \cdot B = 0$                          | - | - | - | -   |
| $\nabla \times B - \frac{1}{c} \frac{\partial E}{\partial t} = \frac{4\pi}{c} j$ | - | - | - | -   |
| $\nabla \times E + \frac{1}{c} \frac{\partial B}{\partial t} = 0$ | + | + | - | -   |

tation of CP asymmetry in nature, the baryon asymmetry of the Universe? This brief review is devoted to these questions.

In Section II we introduce the discrete symmetries P, T, and C by the example of Maxwell’s equations. Section III is devoted to the history and present status of CP violation and related phenomena in kaon decays, while Section IV deals with results and prospects for $B$ mesons. Some future measurements are discussed in Section V. The baryon number of the Universe and its relation to CP violation are treated briefly in Section VI, while Section VII concludes.

II DISCRETE SYMMETRIES

Maxwell’s equations in vacuum provide a convenient framework for illustrating the action of discrete symmetries, since each term in each equation must transform similarly.

Under P, we have $E(x,t) \rightarrow -E(-x,t)$, $B(x,t) \rightarrow B(-x,t)$, $\nabla \rightarrow -\nabla$, $j(x,t) \rightarrow -j(-x,t)$, i.e., electric fields change in sign while magnetic fields do not, and currents change in direction. Under time reversal, $E(x,t) \rightarrow E(x,-t)$, $B(x,t) \rightarrow -B(x,-t)$, $\partial/\partial t \rightarrow -\partial/\partial t$, $j(x,t) \rightarrow -j(x,-t)$, i.e., magnetic fields change in sign while electric fields do not, since directions of currents are reversed. Under C, $E(x,t) \rightarrow -E(x,t)$, $B(x,t) \rightarrow -B(x,t)$, $\rho(x,t) \rightarrow -\rho(x,t)$, $j(x,t) \rightarrow -j(x,t)$, i.e., both electric and magnetic fields retain their signs: $E(x,t) \rightarrow E(-x,-t)$, $B(x,t) = B(-x,-t)$.

The behavior of the Maxwell equations under P, T, C, and CPT is summarized in Table 1. Each term behaves as shown. It is interesting that a fundamental term in the Lagrangian behaving as $E \cdot B$, while Lorentz covariant, violates P and T. The strong suppression of such a term (as evidenced by the small value of the neutron electric dipole moment) is known as the strong CP problem [7], and, although of fundamental importance, will not be discussed further here.
III CP SYMMETRY FOR KAONS

A $K \to \pi\pi$ decays

While some neutral particles (such as $\gamma$, $Z^0$, and $\pi^0$) are equal to their antiparticles, others (such as the neutron) are not. The $K^0$, discovered in cosmic radiation in the late 1940’s [8], is one such particle. It is characterized by an additive quantum number $S = 1$, strangeness, introduced [9] in order to explain its strong production (which conserves strangeness) and weak decay (which does not). The antiparticle of $K^0$, the $\overline{K^0}$, has $S = -1$. Since strangeness is violated in decays, one must appeal to discrete symmetries to describe the linear combinations of $K^0$ and $\overline{K^0}$ corresponding to states of definite mass and lifetime. These states are

$$K_1 = \frac{K^0 + \overline{K^0}}{\sqrt{2}}, \quad K_2 = \frac{K^0 - \overline{K^0}}{\sqrt{2}}. \quad (1)$$

The $K_1$ is permitted to decay to $\pi\pi$ and thus should be short-lived, while the $K_2$ is forbidden to decay to $\pi\pi$, must instead decay to $3\pi$, $\pi\ell\nu\ell$, etc., and thus will be longer-lived. Indeed, the short-lived neutral kaon ($\sim K_1$) lives for only 0.089 ns, while the long-lived neutral kaon ($\sim K_2$) lives for 52 ns, nearly a factor of 600 longer.

The original argument by Gell-Mann and Pais [10], based in 1955 on C and P conservation, was recast in 1957 in terms of the product CP [11], to correspond to the newly formulated CP-invariant theory of the weak interactions. The $K^0$ and $\overline{K^0}$ have spin zero. A spin-zero final state of $\pi\pi$ has CP eigenvalue equal to +1. Thus, if CP is conserved, it is the CP-even linear combination of $K^0$ and $\overline{K^0}$ which decays to $\pi\pi$. With a phase convention such that $CP|K^0\rangle = |K^0\rangle$, this is just the combination $K_1$. The Gell-Mann–Pais proposal was soon confirmed [12] by the discovery of the predicted long-lived particle corresponding to $K_2$.

Similar behavior is encountered in many cases of degenerate systems, such as two coupled pendula [13] or a drum-head in its first excited state. In the latter case, the drum has two degenerate modes, each with one nodal line corresponding to a diameter, which will be orthogonal to one another if the corresponding nodal lines are perpendicular to each other. Consider two equally valid bases:

- (B1) Diagonal nodal lines point to the upper right ($R$) and the upper left ($L$).
- (B2) The nodal lines are horizontal ($H$) and vertical ($V$).

We can draw the analogy $R \leftrightarrow K^0$, $L \leftrightarrow \overline{K^0}$. Suppose, now, that a fly alights on the bottom edge of the drum head, such that it sits on the nodal line of the $V$ mode. Then the modes $V$ and $H$ are split from one another. The mode $H = (R + L)/\sqrt{2}$ which couples to the fly will shift in mass and lifetime. It is analogous to $K_1$ and the fly is analogous to the $\pi\pi$ system. The mode $V$ is unaffected by the fly. It is analogous to $K_2$.

In 1964, Christenson, Cronin, Fitch, and Turlay [1], using a spark chamber exposed to a beam of long-lived neutral kaons, found that these particles indeed did decay to $\pi\pi$. For many years this phenomenon could be described in terms of a single parameter $\epsilon$, such that the states of definite mass and lifetime become

$$K_1 \rightarrow K_S \text{ ("short") } \simeq K_1 + \epsilon K_2 \quad , \quad K_2 \rightarrow K_L \text{ ("long") } \simeq K_2 + \epsilon K_1 ,$$

with $|\epsilon| \simeq 2 \times 10^{-3}$, and $\text{Arg}(\epsilon) \simeq \pi/4$. Confirmation of this description was provided by the rate asymmetry in the decays $K_L \rightarrow \pi^\pm \ell^\mp \nu_\ell$, which measures $\text{Re} \epsilon$. But what is the source of $\epsilon$?

One possibility was suggested almost immediately by Wolfenstein [14]: A new “superweak” $|\Delta S = 2|$ interaction could mix $K^0 = \bar{d}s$ and $\bar{K}^0 = s\bar{d}$ (where $d$ and $s$ denote quarks) without any other observable consequences. This theory would imply, for example, that no difference in the ratio of CP-violating and CP-conserving amplitudes would arise when comparing $\pi^+\pi^-$ and $\pi^0\pi^0$ final states.

A new opportunity for generating not only $\epsilon$ but other CP-violating effects as well arises when there are at least three quark families, as first proposed by Kobayashi and Maskawa [3]. Loop diagrams inducing the transition $d\bar{s} \leftrightarrow s\bar{d}$ involving internal lines of $W^+W^-$ and $u,c,t$ quarks and antiquarks can lead to $\epsilon \neq 0$ when the coupling constants are complex. With three quark families, one cannot redefine phases of quarks so that all the couplings are real. Some other consequences of the Kobayashi-Maskawa theory will be mentioned presently.

The time-dependence of the two-component $K^0$ and $\bar{K}^0$ system is governed by a $2 \times 2$ mass matrix $\mathcal{M}$ (for reviews see [15]):

$$i \frac{\partial}{\partial t} \begin{bmatrix} K^0 \\ \bar{K}^0 \end{bmatrix} = \mathcal{M} \begin{bmatrix} K^0 \\ \bar{K}^0 \end{bmatrix} ,$$

where $\mathcal{M} = M - i\Gamma/2$, and $M$ and $\Gamma$ are Hermitian matrices. The eigenstates are, approximately,

$$K_S \simeq K_1 + \epsilon K_2 \quad , \quad K_L \simeq K_2 + \epsilon K_1 ,$$

corresponding to the eigenvalues $\mu_{S,L} = m_{S,L} - i\gamma_{S,L}/2$, with

$$\epsilon \simeq \frac{\text{Im}(\Gamma_{12}/2) + i \text{ Im} M_{12}}{\mu_S - \mu_L} .$$

Using both data and the magnitude of CKM matrix elements one can show [15] that the second term dominates. Since the mass difference $m_L - m_S$ and width difference $\gamma_S - \gamma_L$ are nearly equal, the phase of $\mu_L - \mu_S$ is about $\pi/4$, so that the phase of $\epsilon$ is also $\pi/4$ (mod $\pi$).

It is easy to emulate the CP-conserving neutral kaon system in table-top demonstrations of systems with two degenerate states, such as the pair of coupled pendula
mentioned above [13]. The demonstration of CP violation is harder, requiring systems that emulate \( \text{Im}(M_{12}) \neq 0 \) or \( \text{Im}(\Gamma_{12}) \neq 0 \). One can couple two identical resonant circuits “directionally” to each other so that the energy fed from circuit 1 to circuit 2 differs from that fed in the reverse direction [16]. Devices with this property utilize Faraday rotation of the plane of polarization of radio-frequency waves. More recently, it was realized [17] that this asymmetric coupling is inherent in the equations of motion of a spherical (or “conical”) pendulum in a rotating coordinate system, giving rise to the precession of the plane of oscillation of the Foucault pendulum. In either case the analogy actually deepens the mystery of CP violation, since the CP-violating effect is imposed, so to speak, “from the outside,” using a magnetic field in the case of directional couplers or a rotating coordinate frame in the case of the Foucault pendulum.

To return to the CKM matrix, we have the following parameterization suggested by Wolfenstein [18]:

\[
V = \begin{bmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{bmatrix} = \begin{bmatrix}
1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{bmatrix},
\]

(6)

where \( \lambda = \sin \theta_C \simeq 0.22 \) describes strange particle decays. Here \( \theta_C \) is the Gell-Mann–Lévy–Cabibbo [4,19] angle, originally introduced to preserve the universal strength of the hadronic weak current. The unitarity of the CKM matrix, \( V^\dagger V = V^{-1} \), is the modern way of implementing this requirement.

We learn \( |V_{cb}| = A\lambda^2 \simeq 0.039 \pm 0.003 \) from the dominant decays of \( b \) quarks, which are to charmed quarks [20]. (We have expanded errors somewhat in comparison with those quoted in some reviews [21]. The dominant source of error in many cases is theoretical.) Similarly, charmless \( b \) decays give \( |V_{ub}/V_{cb}| = 0.090 \pm 0.025 = \lambda(\rho^2 + \eta^2)^{1/2} \), leading to a constraint on \( \rho^2 + \eta^2 \).

As a result of the unitarity of the CKM matrix, the quantities \( V_{ub}^*/A\lambda^3 = \rho + i\eta, V_{td}/A\lambda^2 = 1 - \rho - i\eta, \) and 1 form a triangle in the \((\rho, \eta)\) plane (Fig. 1). The angles opposite these sides are, respectively, \( \beta = -\text{Arg}(V_{td}), \gamma = \text{Arg}(V_{ub}^*), \) and \( \alpha = \pi - \beta - \gamma \). We still do not have satisfactory limits on the angle \( \gamma \) (equivalently, on the magnitude of the side \( V_{td} \)) of this “unitarity triangle.” Further information comes from the following constraints (see [22] for more details):

1. The magnitude of \( \epsilon \) constrains mainly the imaginary part of \( V_{ud}^2 \), which is proportional to \( \eta(1 - \rho) \), since the top quark dominates the loop diagram giving rise to \( K^0 - \bar{K}^0 \) mixing. A correction due to charmed quarks changes the 1 to 1.44, with the result \( \eta(1.44 - \rho) = 0.51 \pm 0.18 \).

2. We have taken the amplitude for mixing of the neutral \( B^0 \) meson with its antiparticle \( \bar{B}^0 \) to be \( \Delta m_d = 0.473 \pm 0.016 \text{ ps}^{-1} \) [23]. The subscript \( d \) denotes the light quark in the \( B^0 \). Taking the matrix element of the four-quark operator inducing the relevant \( bd \leftrightarrow \bar{d}b \) transition to be \( f_B \sqrt{B_B} = 200 \pm 40 \text{ MeV} \), we find a constraint on \( |V_{td}| \) which amounts to \( |1 - \rho - i\eta| = 1.01 \pm 0.21 \).
FIGURE 1. Unitarity triangle for CKM elements. Here $\rho + i\eta = V_{ub}^* / A\lambda^3$; $1 - \rho - i\eta = V_{td} / A\lambda^3$.

TABLE 2. Ranges of angles in the unitarity triangle.

| Angle | Expression | Degrees | $\rho$ | $\eta$ |
|-------|------------|---------|--------|--------|
| $\alpha$ | $\pi - \beta - \gamma$ | Min: 72 | -0.01 | 0.30 |
|       |            | Max: 113 | 0.25   | 0.27  |
| $\beta$ | $\tan^{-1}[\rho/(1 - \eta)]$ | Min: 17 | -0.01 | 0.30 |
|       |            | Max: 31  | 0.29   | 0.43  |
| $\gamma$ | $\tan^{-1}(\eta/\rho)$ | Min: 48 | 0.25   | 0.27  |
|        |            | Max: 92  | -0.01  | 0.30  |

3. We have used the following lower limit for mixing of the strange $b$ meson $B_s = \bar{b}s$ with its antiparticle: $\Delta m_s > 14.3 \text{ ps}^{-1}$ (95% c.l.) [23,24]. Since the relevant CKM elements (including $|V_{ts}| = A\lambda^3$) are fairly well known, this result serves mainly to constrain the combination of hadronic parameters $f_{B_s}\sqrt{B_{B_s}}$ and hence, through the assumption $[f_{B_s}\sqrt{B_{B_s}}]/[f_B\sqrt{B_B}] < 1.25$ [25], yields the bound $|V_{ts}/V_{td}| > 4.3$ or $|1 - \rho - i\eta| < 1.05$.

The resulting limits on $(\rho, \eta)$ are a roughly rectangular region bounded on the left by $|1 - \rho - i\eta| < 1.05$, on the top and bottom by $0.3 < (\rho^2 + \eta^2)^{1/2} < 0.52$, and on the right by $|1 - \rho - i\eta| > 0.8$. Only a small region is excluded by the bound arising from the parameter $\epsilon$: $\eta(1.44 - \rho) > 0.33$. Even without this bound, the case of real CKM matrix elements ($\eta = 0$), i.e., a superweak origin for $\epsilon$, is disfavored. The boundaries of this region give rise to the minimum and maximum values of $\alpha, \beta, \gamma$ shown in Table 2. These bounds imply

$$-0.71 < \sin 2\alpha < 0.59, \quad 0.59 < \sin 2\beta < 0.89, \quad 0.54 < \sin^2 \gamma < 1 \quad (7)$$

for quantities which are measurable in $B$ decays (see below). The allowed values of $(\rho, \eta)$ are $\simeq (0.14 \pm 0.15, 0.38 \pm 0.13)$.

The Kobayashi-Maskawa theory predicts small differences in CP-violating decays to pairs of charged and neutral pions. These arise in the following way.
1. “Tree” amplitudes are governed by $\bar{s} \rightarrow \bar{u}u \bar{d}$. Since this subprocess has three nonstrange quarks in the final state, it contributes to both $\Delta I = 1/2$ and $\Delta I = 3/2$ transitions, and hence to both $I_{\pi\pi} = 0$ and $I_{\pi\pi} = 2$ final states. The corresponding CKM matrix elements are real, so these amplitudes do not have a weak phase.

2. “Penguin” amplitudes involve a transition $\bar{s} \rightarrow \bar{d}$ with internal $W$ and $u, c, t$ lines and emission or absorption of a gluon. The subprocess has only one non-strange quark in the final state so it contributes only to $\Delta I = 1/2$ transitions and hence only to the $I_{\pi\pi} = 0$ final state. Because of the presence of all three $Q = 2/3$ quarks in internal lines, these amplitudes have a weak phase.

As a consequence of the different isospin structure and weak phases of the tree and penguin amplitudes, the $I_{\pi\pi} = 0$ and $I_{\pi\pi} = 2$ amplitudes thus acquire different weak phases, leading to a small difference from unity of the ratio

$$R \equiv \frac{\Gamma(K_L \rightarrow \pi^+\pi^-)/\Gamma(K_S \rightarrow \pi^+\pi^-)}{\Gamma(K_L \rightarrow \pi^0\pi^0)/\Gamma(K_S \rightarrow \pi^0\pi^0)} = 1 + 6 \text{ Re} \frac{\epsilon'}{\epsilon}, \quad (8)$$

where $\epsilon'$ is related to the imaginary part of the ratio of the $I_{\pi\pi} = 2$ and $I_{\pi\pi} = 0$ amplitudes. The ratio $\epsilon'/\epsilon$ acquires an important term proportional to the CKM parameter $\eta$ from the penguin contribution. This term is partially canceled by an “electroweak penguin” in which the gluon mentioned above is replaced by a virtual photon or $Z$, whose isospin-dependent couplings to quarks induce $\Delta I = 3/2$ contributions. $\epsilon'/\epsilon$ is expected to be nearly real. Its magnitude was estimated by one group [26] to be a few parts in $10^4$, with a broad and somewhat asymmetric probability distribution extending from slightly below zero to above $2 \times 10^{-3}$. Some other estimates, discussed in Refs. [27], permit higher values.

The most recent experiments on $\text{Re}(\epsilon'/\epsilon)$ are summarized in Table 3. A scale factor [28] of 1.86 is included in the error of the average to account for the large spread in quoted results. The value of $\epsilon'/\epsilon$ is non-zero, with a magnitude in the ballpark of estimates based on the Kobayashi-Maskawa theory. The fact that it is larger than some theoretical estimates is not a serious problem, given that we still
cannot account reliably for the large enhancement of $\Delta I = 1/2$ amplitudes with respect to $\Delta I = 3/2$ amplitudes in \textit{CP-conserving} $K \rightarrow \pi\pi$ decays.

**B Other rare kaon decays**

A CP- or T-violating angular asymmetry in $K_L \rightarrow \pi^+\pi^-e^+e^-$ has recently been reported [31,32]. With a final state consisting of four distinct particles, using the three independent final c.m. momenta, one can construct a T-odd observable whose presence is signaled by a characteristic distribution in the angle $\phi$ between the $\pi^+\pi^-$ and $e^+e^-$ planes.

The asymmetry in $\sin \phi \cos \phi$ reported in Ref. [31] is $(13.6 \pm 2.5 \pm 1.2)\%$. It arises from interference between two processes. (1) The $K_L$ decays to $\pi^+\pi^-$ with an amplitude $\epsilon$. This process is CP-violating. One of the pions then radiates a virtual photon which internally converts to $e^+e^-$. (2) The CP-odd state $K_2$ can decay directly to $\pi^+\pi^-\gamma$ via a weak magnetic dipole transition. This process is CP-conserving.

The decay $K_L \rightarrow \mu^+\mu^-\gamma$ has recently been studied with sufficiently high statistics to permit a greatly improved measurement of the virtual-photon form factor in $K_L \rightarrow \gamma^*\gamma$ [33]. This measurement is useful in estimating the long-distance contribution to the real part of the amplitude in $K_L \rightarrow \gamma^{(*)}\gamma^{(*)} \rightarrow \mu^+\mu^-$, which in turn allows one to limit the short-distance contribution to $K_L \rightarrow \mu^+\mu^-$. Since this contribution involves loops with virtual $W$'s and $u,c,t$ quarks, useful bounds on CKM matrix elements can be placed. Preliminary results [33] indicate $\rho > -0.2$, the best limit so far from any process involving kaons.

Several neutral-current processes involving $K \rightarrow \pi +$ (lepton pair) can shed further light on the Kobayashi-Maskawa theory of CP violation [34].

1. The decay $K^+ \rightarrow \pi^+\nu\bar{\nu}$ is sensitive primarily to $|V_{td}|$, with a small charm correction, and so constrains the combination $|1.4 - \rho - i\eta|$. The predicted branching ratio is roughly

\[ B(K^+ \rightarrow \pi^+\nu\bar{\nu}) \simeq 10^{-10} \left| \frac{1.4 - \rho - i\eta}{1.4} \right|^2 , \quad (9) \]

For $0 \leq \rho \leq 0.3$ one then predicts (see [34]) $B(K^+ \rightarrow \pi^+\nu\bar{\nu}) = (0.8 \pm 0.2) \times 10^{-10}$, with additional uncertainties associated with the charmed quark mass and the magnitude of $V_{cb}$. A measurement of this branching ratio with an accuracy of 10% is of high priority in constraining $(\rho, \eta)$ further.

The Brookhaven E787 Collaboration has reported one event with negligible background [35], corresponding to

\[ B(K^+ \rightarrow \pi^+\nu\bar{\nu}) = (1.5^{+3.4}_{-1.2}) \times 10^{-10} . \quad (10) \]

More data are expected from the final stages of analysis of this experiment, as well as from a future version (Brookhaven E949) with improved sensitivity.
2. The decays $K_L \to \pi^0 \ell^+ \ell^-$ are expected to be dominated by CP-violating contributions, both indirect ($\sim \epsilon$) and direct. There is also a CP-conserving “contaminant” from the intermediate state $K_L \to \pi^0 \gamma \gamma$. The direct contribution probes the CKM parameter $\eta$. It is expected to be comparable in magnitude to the indirect contribution, and to have a phase of about $\pi/4$ with respect to it. Each contribution (including the CP-conserving one) is expected to correspond to a $\pi^0 e^+ e^-$ branching ratio of a few parts in $10^{12}$. However, the decay $K_L \to \pi^0 e^+ e^-$ may be limited by backgrounds in the $\gamma \gamma e^+ e^-$ final state associated with radiation of a photon in $K_L \to \gamma e^+ e^-$ from one of the leptons [36]. Present experimental upper limits (90% c.l.) [37] are

$$B(K_L \to \pi^0 e^+ e^-) < 5.64 \times 10^{-10}, \quad B(K_L \to \pi^0 \mu^+ \mu^-) < 3.4 \times 10^{-10} \quad (11)$$

still significantly above theoretical expectations.

3. The decay $K_L \to \pi^0 \nu \bar{\nu}$ is expected to be due entirely to CP violation, and provides a clean probe of $\eta$. Its branching ratio, proportional to $A^4 \eta^2$, is expected to be about $3 \times 10^{-11}$. The best current experimental upper limit (90% c.l.) for this process [38] is $B(K_L \to \pi^0 \nu \bar{\nu}) < 5.9 \times 10^{-7}$, several orders of magnitude above the expected value.

C Is the CKM picture of CP violation right?

Two key tests have been passed so far. The theory has succeeded, albeit qualitatively, in predicting the range $\text{Re}(\epsilon'/\epsilon) = (1\) to 2\) \times 10^{-3}$. Its prediction for the branching ratio for $K^+ \to \pi^+ \nu \bar{\nu}$ is in accord with the experimental rate deduced from the one event observed so far.

One test still to be passed in the decays of neutral kaons is the measurement of the height $\eta$ of the unitarity triangle through the decay $K_L \to \pi^0 \nu \bar{\nu}$. Prospects for this measurement will be mentioned below. However, in the nearer term, one looks forward to a rich set of effects in decays of particles containing $b$ quarks, particularly the $B$ mesons. To this end, experiments are under way at a number of laboratories around the world.

Asymmetric $e^+ e^-$ collisions are being studied at two “$B$ factories,” the PEP-II machine at SLAC with the BaBar detector, and the KEK-B collider in Japan with the Belle detector. By end of April 2000, these detectors were recording about 100 and 60 pb$^{-1}$ of data per day, respectively, and had accumulated about 6 and 2 fb$^{-1}$ of data at the energy of the $\Upsilon(4S)$ resonance, which decays almost exclusively to $B \bar{B}$. The BaBar experiment expects to have about 100 tagged $B^0 \to J/\psi K_S$ decays by this coming summer [39].

Significant further data on $e^+ e^-$ collisions at the $\Upsilon(4S)$ are expected from the Cornell Electron Storage Ring with the upgraded CLEO-III detector. The HERA-b experiment at DESY in Hamburg will study $b$ quark production via the collisions of 920 GeV protons with a fixed target. The CDF and D0 detectors at Fermilab will
devote a significant part of their program at Run II of the Tevatron to $B$ physics. In the longer term, one can expect further results on $B$ physics from the general-purpose LHC detectors ATLAS and CMS and the dedicated LHC-b detector at CERN, and possibly the dedicated BTeV detector at Fermilab.

IV CP VIOLATION AND $B$ DECAYS

In constrast to the neutral kaon system, in which the eigenstates of the mass matrix differ in lifetime by nearly a factor of 600, the eigenstates of the corresponding $B^0$–$ar{B}^0$ mass matrix are expected to differ in lifetime by at most 10–20% for strange $B$’s [40], and considerably less for nonstrange $B$’s. Thus, instead of studying the properties of mass eigenstates like $K_L$, one must resort to other means. There are two main avenues of study.

- **Decays to CP eigenstates** $f = \pm \text{CP}(f)$ utilize interference between direct decays $B^0 \to f$ or $\bar{B}^0 \to f$ and the corresponding paths involving mixing: $B^0 \to \bar{B}^0 \to f$ or $\bar{B}^0 \to B^0 \to f$. Final states such as $f = J/\psi K_S$ provide “clean” examples in which one quark subprocess is dominant. In this case one measures $\sin 2\beta$ with negligible corrections. For the final state $\pi^+\pi^-$, one measures $\sin 2\alpha$ only to the extent that the direct decay is dominated by a “tree” amplitude (the quark subprocess $b \to u\bar{d}d$). When contamination from the penguin subprocess $b \to d$ is present (as it is expected to be at the level of several tens of percent), one must measure decays to other $\pi\pi$ states (such as $\pi^\pm\pi^0$ and $\pi^0\pi^0$) to sort out various decay amplitudes [41].

- **“Self-tagging” decays** involve final states $f$ such as $K^+\pi^-$ which can be distinguished from their CP-conjugates $\bar{f}$. A CP-violating rate asymmetry arises if there exist two weak amplitudes $a_i$ with weak phases $\phi_i$ and strong phases $\delta_i$ ($i = 1, 2$):

\begin{equation}
A(B \to f) = a_1 e^{i(\phi_1 + \delta_1)} + a_2 e^{i(\phi_2 + \delta_2)} ,
\end{equation}

\begin{equation}
A(\bar{B} \to \bar{f}) = a_1 e^{i(\phi_1 + \delta_1)} + a_2 e^{i(\phi_2 + \delta_2)} .
\end{equation}

Note that the weak phase changes sign under CP-conjugation, while the strong phase does not. The rate asymmetry is then

\begin{equation}
\mathcal{A}(f) \equiv \frac{\Gamma(f) - \Gamma(\bar{f})}{\Gamma(f) + \Gamma(\bar{f})} = \frac{2a_1a_2 \sin(\phi_1 - \phi_2) \sin(\delta_1 - \delta_2)}{a_1^2 + a_2^2 + 2a_1a_2 \cos(\phi_1 - \phi_2) \cos(\delta_1 - \delta_2)} .
\end{equation}

Thus the two amplitudes must have different weak and strong phases in order for a rate asymmetry to be observable. The CKM theory predicts the weak phases, but no reliable estimates of strong phases in $B$ decays exist. Some ways of circumventing this difficulty will be mentioned.
A Decays to CP eigenstates

The interference between mixing and decay in decays of neutral $B$ mesons to CP eigenstates leads to a term which modulates the exponential decay (see, e.g., [42]):

$$\frac{d\Gamma(t)}{dt} \sim e^{-\Gamma t} (1 \mp \text{Im} \lambda_0 \sin \Delta mt) ,$$

where the upper sign refers to $B^0$ decays and the lower to $\bar{B}^0$ decays. $\Delta m$ is the mass splitting mentioned earlier, and the factor $\lambda_0$ expresses the interference of decay and mixing amplitudes. For $f = J/\psi K_S$, $\lambda_0 = -e^{-2i\beta}$ to a good approximation, while for $f = \pi^+\pi^-$, $\lambda_0 \simeq e^{2i\alpha}$ only to the extent that the effect of penguin amplitudes can be neglected in comparison with the dominant tree contribution.

The time integral of the modulation term is

$$\int_0^\infty dt e^{-\Gamma t} \sin \Delta mt = \frac{1}{\Gamma} \frac{x}{1 + x^2} \leq \frac{1}{\Gamma} \cdot \frac{1}{2} ,$$

where $x \equiv \Delta m/\Gamma$. This expression is maximum for $x = 1$, and 95% of maximum for the observed value $x \simeq 0.72$. It has been fortunate that the $B^0$ mixing amplitude and decay rate are so well matched to one another.

The CDF Collaboration [43] has learned how to “tag” neutral $B$ mesons at the time of their production and thus to measure the decay rate asymmetry in $B^0 (\bar{B}^0) \rightarrow J/\psi K_S$. This asymmetry arises from the phase $2\beta$ characterizing the two powers of $V_{td}$ in the $B^0-\bar{B}^0$ mixing amplitude. The tagging methods are of two main types. “Opposite-side” methods rely on the fact that strong interactions always produce $b$ and $\bar{b}$ in pairs, so that in order to determine the initial flavor of a decaying $B$ one must find out something about the “other” $b$-containing hadron produced in association with it, either via the charge of the jet containing it or via the charge of the lepton or kaon it emits when decaying. “Same-side” methods [44] utilize the fact that a $B^0$ tends to be associated more frequently with a $\pi^+$, and a $\bar{B}^0$ with a $\pi^-$, somewhere nearby in phase space, whether through the dynamics of fragmentation or through the decays of excited $B$ resonances.

The CDF result is $\sin 2\beta = 0.79^{+0.41}_{-0.40}$. An earlier result from OPAL [45] and a newer result from ALEPH [46], both utilizing $B$’s produced in the decays of the $Z^0$, can be combined with the CDF value to obtain $\sin 2\beta = 0.91 \pm 0.35$, which exceeds zero at the 99% confidence level [46]. At the 1σ lower limit (0.56) this is very close to the lower bound (0.59) quoted in Table 2.

B “Self-tagging” decays and direct CP violation

An example of direct CP violation can occur in $B^0 \rightarrow K^+\pi^-$. One expects two types of contribution to this process: a “tree” amplitude governed by the quark subprocess $\bar{b} \rightarrow \bar{u}u s$ with CKM factor $V_{ts}^* V_{us}$, and a “penguin” amplitude governed
by the quark subprocess $\bar{b} \to \bar{s}$ with dominant CKM factor $V_{tb}^*V_{ts}$ (since the contribution of the top quark in the internal loop is dominant). These contributions are summarized in Table 4.

Since the tree and penguin amplitudes have a relative weak phase $\gamma$ (mod $\pi$), one can have $\Gamma(B^0 \to K^+\pi^-) \neq \Gamma(B^0 \to K^-\pi^+)$ as long as the strong phases $\delta_T$ and $\delta_P$ are different in the tree and penguin amplitudes. However, even if these strong phases do not differ from one another, the ratios of rates for various charge states of $B \to K\pi$ decays can provide separate information on the weak phase $\gamma$ [47–49] and the strong phase difference $\delta_T - \delta_P$.

One must first deal with electroweak penguins which were also relevant for the interpretation of $\epsilon'/\epsilon$. An early suggestion (see the first of Refs. [47]) proposed a way to extract $\gamma$ from the rates for $B^+ \to (\pi^0 K^+, \pi^+ K^0, \pi^+\pi^0)$ and the charge-conjugate processes. The amplitudes for the first two processes (with appropriate factors of $\sqrt{2}$) form a triangle with an amplitude related to the third process by flavor SU(3) as long as electroweak penguins are negligible, which they are not [50]. It turns out, however [49], that the relevant electroweak penguin’s contribution to this process can be calculated, so that sufficiently precise measurements of the rates for the above processes can indeed yield useful information on $\gamma$.

The possibility has been raised recently [49,51,52] that the weak phase $\gamma$ may exceed $90^\circ$. Two processes whose rates hint at this constraint are $B^0 \to \pi^+\pi^-$ and $B^0 \to K^{*+}\pi^-$. The former process has a rate which is somewhat smaller than expected, while the rate for the latter is larger than expected.

The amplitudes contributing to $B^0 \to \pi^+\pi^-$ are summarized in Table 5. The relative phase of the tree and penguin amplitudes is $\gamma + \beta = \pi - \alpha$. The two amplitudes will interfere destructively if the final strong phase difference is small (as expected from perturbative QCD estimates, which indeed may be risky), and if $\alpha < \pi/2$. This would tend to favor not-too-positive values of $\rho$. There is some hint that the interference is indeed destructive. The observed branching ratio [53] $B(B^0 \to \pi^+\pi^-) = (4.3^{+1.6}_{-1.4} \pm 0.5) \times 10^{-6}$ is less than the value of about $10^{-5}$ which one would estimate [51] from the tree amplitude alone (e.g., using the observed $B \to \pi\nu\ell$ branching ratio and factorization).

The same types of amplitudes contributing to $B^0 \to K^+\pi^-$ also contribute to $B^0 \to K^{*+}\pi^-$ (see Table 4). As in $B^0 \to K^+\pi^-$, the relative phase between the tree and penguin amplitudes is expected to be $\gamma - \pi$. One thus expects constructive

| Amplitude | Subprocess | CKM factor | Weak phase |
|-----------|------------|------------|------------|
| Tree      | $\bar{b} \to \bar{u}\bar{s}$ | $V_{ub}^*V_{us}$ | $\gamma$   |
| Penguin   | $\bar{b} \to \bar{s}$ | $V_{tb}^*V_{ts}$ | $\pi$      |
TABLE 5. Main amplitudes contributing to \( B^0 \to \pi^+\pi^- \).

| Amplitude | Subprocess | CKM factor | Weak phase |
|-----------|------------|------------|------------|
| Tree      | \( \bar{b} \to \bar{u}ud \) | \( V_{ub}^*V_{ud} \) | \( \gamma \) |
| Penguin   | \( \bar{b} \to \bar{d} \) | \( V_{tb}^*V_{td} \) | \( -\beta \) |

interference between the two amplitudes if the strong phase difference is small and \( \gamma > \pi/2 \). Indeed, the branching ratio for \( B^0 \to K^{*+}\pi^- \) appears to exceed \( 2 \times 10^{-5} \), while the pure “penguin” process \( B^+ \to K^+\phi \) has a branching ratio less than \( 10^{-5} \).

A global fit to the above two processes and many others (see the second of Refs. [52]) finds \( \gamma = (114_{-23}^{+24})^\circ \), which just grazes the allowed region quoted in Table 2. Since the upper bound on \( \gamma \) in Table 2 is set primarily by the lower limit on \( B_s^-\bar{B}_s^- \) mixing, such mixing should be visible in experiments of only slightly greater sensitivity than those performed up to now.

The Tevatron and the LHC will copiously produce both nonstrange and strange neutral \( B \)'s, decaying to \( \pi^+\pi^- \), \( K^\pm\pi^\mp \), and \( K^+K^- \) [54]. Each of these channels has particular advantages.

- The decays \( B^0 \to K^+K^- \) and \( B_s \to \pi^+\pi^- \) should be highly suppressed unless these final states are “fed” by rescattering from other channels [55].

- The decays \( B^0 \to \pi^+\pi^- \) and \( B_s \to K^+K^- \) can yield \( \gamma \) when their time-dependence is measured [56]. The kinematic peaks for these two states overlap significantly, so one must either use particle identification or utilize the vastly different oscillation frequencies for \( B^0^-\bar{B}^0 \) and \( B_s^-\bar{B}_s \) mixing to distinguish the two final states.

- A recent proposal for measuring \( \gamma \) [57] utilizes the decays \( B^0 \to K^+\pi^- \), \( B^+ \to K^0\pi^+ \), \( B_s \to K^-\pi^+ \), and the corresponding charge-conjugate processes. The \( B^0 \to K^+\pi^- \) and \( B_s \to K^-\pi^+ \) peaks are well separated from one another and from \( B^0 \to \pi^+\pi^- \) and \( B_s \to K^+K^- \) kinematically [54].

The proposal of Ref. [57] is based on the observation that \( B \to K\pi \) decays involve two types of amplitudes, tree \( (T) \) and penguin \( (P) \), with relative weak phase \( \gamma \) and relative strong phase \( \delta \). The decays \( B^+ \to K^0\pi^+ \) are expected to be dominated by the penguin amplitude (there is no tree contribution except through rescattering from other final states), so this channel is not expected to display any CP-violating asymmetries. One expects \( \Gamma(B^+ \to K^0\pi^+) = \Gamma(B^- \to K^0\pi^-) \). This will provide a check of the assumption that rescattering effects can be neglected. A typical amplitude is given by \( A(B^0 \to K^+\pi^-) = -[P + T e^{i(\gamma+\delta)}] \), where the signs are associated with phase conventions for states [58].

We now define
TABLE 6. CP-violating asymmetries in decays of $B$ mesons to light quarks.

| Mode     | Signal events | $\mathcal{A}_{CP}$       |
|----------|---------------|--------------------------|
| $K^+\pi^-$ | $80^{+12}_{-11}$ | $-0.04 \pm 0.16$        |
| $K^+\pi^0$ | $42.1^{+10.9}_{-9.9}$ | $-0.29 \pm 0.23$        |
| $K_S\pi^+$ | $25.2^{+6.4}_{-5.6}$ | $+0.18 \pm 0.24$        |
| $K^+\eta'$ | $100^{+13}_{-12}$ | $+0.03 \pm 0.12$        |
| $\omega\pi^+$ | $28.5^{+8.2}_{-7.3}$ | $-0.34 \pm 0.25$        |

\[
\left\{ \begin{array}{l}
R \\
A_0
\end{array} \right\} \equiv \frac{\Gamma(B^0 \to K^+\pi^-) \pm \Gamma(B^0 \to K^-\pi^+)}{2\Gamma(B^+ \to K^0\pi^+)} ,
\]

\[
\left\{ \begin{array}{l}
R_s \\
A_s
\end{array} \right\} \equiv \frac{\Gamma(B_s \to K^-\pi^+) \pm \Gamma(B_s \to K^+\pi^-)}{2\Gamma(B^+ \to K^0\pi^+)} ,
\]

and $r \equiv T/P$, $\bar{\lambda} \equiv V_{us}/V_{ud}$. Then one finds

\[
R = 1 + r^2 + 2r \cos \delta \cos \gamma , \quad R_s = \bar{\lambda}^2 + \left( \frac{r}{\bar{\lambda}} \right)^2 - 2r \cos \delta \cos \gamma ,
\]

\[
A_0 = -A_s = -2r \sin \gamma \sin \delta .
\]

The sum of $R$ and $R_s$ allows one to determine $r$. Then using $R$, $r$, and $A_0$, one can solve for both $\delta$ and $\gamma$. The prediction $A_s = -A_0$ serves as a check of the flavor SU(3) assumption which gave these relations. An error of $10^\circ$ on $\gamma$ seems feasible with forthcoming data from Run II of the Tevatron.

The CLEO Collaboration has recently presented some upper limits on CP-violating asymmetries in $B$ decays to light-quark systems [59], based on $9.66$ million events recorded at the $\Upsilon(4S)$. With asymmetries defined as

\[
\mathcal{A}_{CP} \equiv \frac{\Gamma(B \to \bar{f}) - \Gamma(B \to f)}{\Gamma(B \to \bar{f}) + \Gamma(B \to f)} ,
\]

the results are shown in Table 6. No statistically significant asymmetries have been seen yet. The sensitivity of these results is not yet adequate to probe the maximum predicted values [60] $|\mathcal{A}_{CP}^{K^+\pi^+}| \leq 1/3$, but is getting close.
V SOME FUTURE MEASUREMENTS

The future of the experimental study of CP violation involves a broad program of experiments with kaons, charmed and $B$ mesons, and neutrinos. We mention just a few of the possibilities.

A Rare kaon decays

Plans are afoot for measurement of the branching ratio for $K_L \rightarrow \pi^0\nu\bar{\nu}$ at the required sensitivity ($B \simeq 3 \times 10^{-3}$). Experiments are envisioned using both relatively slow kaons at Brookhaven National Laboratory [61] and faster kaons at the Fermilab Main Injector [62]. A Fermilab proposal [63] seeks to accumulate 100 events of $K^+ \rightarrow \pi^+\nu\bar{\nu}$ in order to measure $|V_{td}|$ to a statistical precision of 5% and an overall precision of 10%.

B Charmed mesons

Impressive strides have been taken in the measurement of mass differences and lifetime differences for CP eigenstates of the neutral charmed mesons $D^0$ [64,65]. No significant effects have been seen yet at the level of a percent or so, but there are tantalizing hints [66]. It would be worth while to follow up these possibilities. Electron-positron colliders, mentioned below, will devote much of their running time to the study of $B$ mesons, but charmed mesons are accumulated as well in such experiments, and the samples of them will increase. Hadronic experiments dedicated to producing large numbers of $B$’s may also have more to say about mixing, lifetime differences, and CP violation for charmed mesons.

C $B$ production in symmetric $e^+e^-$ collisions

Although asymmetric $e^+e^-$ colliders, known as “B-factories,” are now starting to take data at an impressive rate, the CLEO Collaboration at the symmetric CESR machine has recently celebrated 20 years of $B$ physics, and is continuing with an active program. It will be able in the CLEO-III program to probe charmless $B$ decays down to branching ratios of $10^{-6}$. In so doing, it may be able to detect the elusive $B^0 \rightarrow \pi^0\pi^0$ mode, whose rate will help pin down the penguin amplitude’s contribution and permit a determination of the CKM phase $\alpha$ [41].

Other final states of great interest at this level include $VP$ and $VV$, where $P, V$ denote light pseudoscalar and vector mesons. There is a good chance that direct CP violation may show up in one or more channels if final state phase differences are sufficiently large. The detailed study of angular correlations in $VV$ channels may be able to provide useful information on strong final state phases.
A useful probe of rescattering effects [55], mentioned above, is the decay $B^0 \rightarrow K^+K^-$. This decay is expected to have a branching ratio of only a few parts in $10^8$ if rescattering is unimportant, but could be enhanced by more than an order of magnitude in the presence of rescattering from other channels.

A challenging channel of fundamental importance is $B^+ \rightarrow \tau^+\bar{\nu}_\tau$. The rate for this process will provide information on the combination $f_B|V_{cb}|$. Rare decays which have not yet been seen (such as $B \rightarrow X\ell^+\ell^-$ and $B \rightarrow X\nu\bar{\nu}$) will probe the effects of new particles in loops.

D  

**$B$ production in asymmetric $e^+e^-$ collisions**

The benchmark process for the BaBar and Belle detectors will be the measurement of $\sin 2\beta$ in $B^0 \rightarrow J/\psi K_S$. The PEP-II and KEK-B machines utilize asymmetric $e^+e^-$ collisions in order to create a moving reference frame in which the decays of $B^0$ and $\bar{B}^0$ are separated by a large enough distance for their separation to be detectable. (Each travels only an average distance of 30 $\mu$m in the center of mass.) This facilitates both flavor tagging and improvement of signal with respect to background. These machines will make possible a host of time-dependent studies in such decays as $B \rightarrow \pi\pi$, $B \rightarrow K\pi$, etc., and their impressive luminosities will eventually add significantly to the world’s tally of detected $B$’s.

E  

**Hadronic $B$ production**

The strange $B$’s cannot be produced at the $\Upsilon(4S)$ which will dominate the attention of $e^+e^-$ colliders for some years to come. Hadronic reactions at high energies will produce copious $b$’s incorporated into all sorts of hadrons: nonstrange, strange, and charmed mesons, and baryons. One looks forward to a measurement of the strange-$B$ mixing parameter $x_s = \Delta m_s/\Gamma_s$. The decays of $B_s$ can provide valuable information on CKM phases and CP violation, as in $B_s \rightarrow K^+K^-$ [56]. The width difference of 10–20% expected between the CP-even and CP-odd eigenstates of the $B_s$ system [40] should be visible in the next round of experiments.

F  

**Neutrino studies**

The origin of magnitudes and phases in the CKM matrix is intimately connected with the origin of the quark masses themselves, whose physics still eludes us. We will not understand this pattern until we have mapped out a similar pattern for the leptons, a topic to which many other talks in this Workshop are devoted. Our understanding of neutrino masses and mixings will benefit greatly from forthcoming experiments at the Sudbury Neutrino Observatory [67], Borexino [68], K2K [69], and Fermilab (BooNE and MINOS) [70], to name a few.
FIGURE 2. Example of a region in the $(\rho, \eta)$ plane that might be allowed by data in the year 2003. Constraints are based on the following assumptions: $|V_{ub}/V_{cb}| = 0.08 \pm 0.008$ (solid semicircles), $|V_{ub}/V_{td}| = |(\rho - i\eta)/(1 - \rho - i\eta)| = 0.362 \pm 0.036$ based on present data on $B^0 - \bar{B}^0$ mixing and a measurement of $B(B^+ \rightarrow \tau^+ \nu_\tau)$ to $\pm 20\%$ (dashed semicircles), CP-violating $K - \bar{K}$ mixing as discussed in Sec. 2 but with $V_{cb}$ measured to $\pm 4\%$ (dotted hyperbolae), the bound $x_s > 20$ for $B^0_s - \bar{B}^0_s$ mixing (to the right of the dot-dashed semicircle), and measurement of $\sin 2\beta$ to $\pm 0.059$ (diagonal straight lines). The plotted point, corresponding to $(\rho, \eta) = (0.06, 0.36)$, lies roughly within the center of the allowed region.

G The $(\rho, \eta)$ plot in a few years

The $(\rho, \eta)$ plot might appear as shown in Fig. 2 in a few years [22,71]. We can look forward either to a reliable determination of parameters or to the possibility that one or more experiments give contradictory results, indicating the need for new physics. Such new physics most typically shows up in the form of additional contributions to $B^0 - \bar{B}^0$ mixing [72], though it can also show up in decays [73].

VI BARYON ASYMMETRY

The ratio of the number of baryons $n_B$ to the number of photons $n_\gamma$ in the Universe is a few parts in $10^{10}$, much larger than the corresponding ratio for antibaryons. Shortly after the discovery of CP violation in neutral kaon decays, Sakharov proposed in 1967 [74] three ingredients needed to understand this preponderance of matter over antimatter: (1) an epoch in which the Universe was not in thermal equilibrium, (2) an interaction violating baryon number, and (3) CP (and C) violation. However, one can’t explain the observed baryon asymmetry
merely by means of the CP violation contained in the CKM matrix. The effects are too small unless some new physics is introduced. Two examples are the following:

- The concept of supersymmetry, in which each particle of spin $J$ has a “superpartner” of spin $J \pm 1/2$, affords many opportunities for introducing new CP-violating phases and interactions which could affect particle-antiparticle mixing [75].

- The presence of neutrino masses at the sub-eV level can signal large Majorana masses for right-hand neutrinos, exceeding $10^{11}$ GeV [76]. Lepton number ($L$) is violated by such masses. The violation of $L$ can easily be reprocessed into baryon number ($B$) violation by $B - L$ conserving interactions at the electroweak scale [77]. New CP-violating interactions must then exist at the high mass scale if lepton number is to be generated there. It is conceivable that these interactions are related to CKM phases, but the link will be very indirect [78]. In any case, if this alternative is the correct one, it will be very important to understand the leptonic analogue of the CKM matrix!

VII CONCLUSIONS

The CKM theory of CP violation in neutral kaon decays has passed a crucial test. The parameter $\epsilon'/\epsilon$ is nonzero, and has the expected order of magnitude, though exceeding some theoretical estimates. Still to come will be several tests using $B$ mesons, including the observation of a difference in rates between $B^0 \to J/\psi K_S$ and $\bar{B}^0 \to J/\psi K_S$. There will be more progress in “tagging” neutral $B$’s, and we can look forward to rich information from measurements of decay rates of charged and neutral $B$’s into a variety of final states.

I see two possibilities for our understanding of CP violation in the next few years. (1) If $B$ decays do not provide a consistent set of CKM phases, we will be led to examine other sources of CP violation. Most of these, in contrast to the CKM theory, predict neutron and electron dipole moments very close to their present experimental upper limits. (2) If, on the other hand, the CKM picture still hangs together after a few years, attention should naturally shift to the next “layer of the onion”: the origin of the CKM phases (and the associated quark and lepton masses). It is probably time to start anticipating this possibility, given the resilience of the CKM picture since it was first proposed nearly 30 years ago.

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