ABSTRACT

If CP violation in the decays of neutral kaons is due to phases in the weak couplings of quarks, as encoded in the Cabibbo-Kobayashi-Maskawa (CKM) matrix, there are many other experimental consequences. Notable among these are CP-violating rate asymmetries and triangle relations among decay rates in $B$ meson decays, while charmed particle decays should not be a good place to see CP-violating effects. In the context of the CKM and other models of CP violation, we discuss phenomena such as electric dipole moments, the baryon asymmetry of the Universe, and the strong CP problem, and speculate on a common origin for CP-violating phenomena.

1. Introduction

A crucial step in the formulation of the theory of weak interactions was the realization that parity (P) and charge conjugation (C) were not conserved. The theory as formulated in 1957 did conserve the product CP. Seven years later, the discovery of the two-pion decay of the neutral kaon showed that even the product CP was violated. Since 1964, although no new CP-violating phenomena have been observed, we have a theory for this effect and the prospect of many experimental tests. This review describes our present understanding of CP violation and some of the tests which are likely to bear fruit in the near future.

We begin in Section 2 by discussing present information on CP violation in the system of neutral kaons. Although no direct evidence bearing on the CKM theory has been obtained, there are new results exhibiting greater consistency with invariance under the product CPT, where T stands for time reversal. This is encouraging, since once cannot write a CPT-violating theory without violating cherished properties of quantum field theory.

The leading candidate for CP violation in the kaon system is the presence of phases in the CKM matrix, described in Section 3. Present information allows one to specify a range of parameters for which the theory provides a self-consistent description of both $B - \bar{B}$ and CP-violating $K - \bar{K}$ mixing. Ways in which these parameters can be specified more precisely are described in Section 4. These include further studies of kaons, and numerous experiments on $B$ mesons treated separately in Section 5.

Even though the CKM theory works so well, there are alternative possibilities for CP violation, some of which are described in Section 6. Although the standard CKM picture predicts minuscule effects of CP violation in the charm sector, as
mentioned in Section 7, these effects could be larger in some of the other theories (notably multi-Higgs models).

Although the only direct manifestation of CP violation appears in the neutral kaon system, there is indirect evidence from the existence of a non-zero baryon number in the Universe.\footnote{In Section 8 we comment on one likely scenario for the origin both of the CP violation in the kaon system and the CP violation needed to produce an excess of baryons over antibaryons.}

One place in which CP violation could have shown up, but doesn’t, is in the strong interactions. The structure of the vacuum could have led to measurable CP-violating effects, for example in the electric dipole moment of the neutron. One way to avoid such effects is through a spontaneously broken symmetry\footnote{and the existence of a light pseudoscalar particle.} and the existence of a light pseudoscalar particle.\footnote{Section 9 contains some brief remarks on searches for this particle.}

We summarize in Section 10.

2. The kaon system

2.1. States of definite lifetime

The strangeness hypothesis requires there to be two distinct neutral kaons: a $K^0$ and a $\bar{K}^0$. Since they are degenerate, how can one tell them apart? The weak interactions split linear combinations of these states into ones with definite mass and lifetime. In the limit of CP conservation, one state, $K_1 \equiv (K^0 + \bar{K}^0)/\sqrt{2}$, with even CP, can couple to the CP-even $2\pi$ state, and thus is short-lived. The other, $K_2 \equiv (K^0 - \bar{K}^0)/\sqrt{2}$, with odd CP, is long-lived, since it cannot decay to $2\pi$ but only to three-body final states.\footnote{The discovery in 1964 that the long-lived neutral kaon also decays to $2\pi$ showed that CP is not a valid symmetry of the weak interactions. The short-lived and long-lived states of definite mass and lifetime can be written as}

$$K_S \simeq K_1 + \epsilon K_2$$
$$K_L \simeq K_2 + \epsilon K_1,$$ \hspace{1cm} (1)

where $\epsilon$ encodes all we know at present about CP violation. It is helpful to discuss briefly the phenomenology of the neutral kaon system. Much more complete discussions may be found, for example, in several reviews.\footnote{A detailed investigation of final states in neutral}

2.2. Kaon mixing and phases

In a two-component basis labeled by $K^0$ and $\bar{K}^0$, the mass matrix $\mathcal{M}$ has eigenstates $|S\rangle \equiv |K_S\rangle$ and $|L\rangle \equiv |K_L\rangle$ with corresponding complex eigenvalues $\mu_{S,L} = m_{S,L} - i\gamma_{S,L}/2$. One can decompose $\mathcal{M}$ in terms of two Hermitian matrices $M$ and $\Gamma$: $\mathcal{M} = M - i\Gamma/2$. The requirement of CPT invariance (which we shall assume here) implies $\mathcal{M}_{11} = \mathcal{M}_{22}$.
kaon decays$^4$ shows that one can write $\epsilon \simeq i \text{ Im } M_{12}/(\mu_S - \mu_L)$; an additional contribution from $\text{ Im } \Gamma_{12}$ turns out to be negligible. Consequently, the measured differences between masses and lifetimes of the weak eigenstates allow one to conclude that $\text{ Arg } \epsilon = 43.3^\circ$. Studies of CP-violating kaon decays have shown that $|\epsilon| = (2.26 \pm 0.02) \times 10^{-3}$.

The ratios of amplitudes for long-lived and short-lived decays of kaons to two pions are

$$\eta_{+-} = \frac{A(K_L \rightarrow \pi^+\pi^-)}{A(K_S \rightarrow \pi^+\pi^-)} = \epsilon + \epsilon', \quad \eta_{00} = \frac{A(K_L \rightarrow \pi^0\pi^0)}{A(K_S \rightarrow \pi^0\pi^0)} = \epsilon - 2\epsilon' \ , \quad (2)$$

where

$$\epsilon' = \frac{i \text{ Im } A_s e^{i(\delta_2 - \delta_0)}}{\sqrt{2} A_0} \ . \quad (3)$$

Here the subscripts $I = 0, 2$ on the amplitudes $A_I$ and the elastic phase shifts $\delta_I$ refer to the isospin of the $\pi\pi$ system. The measured phase shifts$^4$ imply that $\text{ Arg } \epsilon' = (43 \pm 6)^\circ$, very close to the expected phase of $\epsilon$. Consequently, one expects nearly maximal constructive or destructive interference between $\epsilon$ and $\epsilon'$ in the ratios of decay rates for $K_L$ and $K_S$ to decay to pairs of charged and neutral pions.

The quantity $\text{ Arg } \epsilon = 43.3^\circ$ is sometimes called the “superweak” phase, since it is that which $\eta_{+-}$ and $\eta_{00}$ would have in a theory$^3$ in which CP violation arose purely from a “superweak” mixing between $K^0$ and $\bar{K}^0$. Since the phase of $\epsilon'$ is expected to be so close to that of $\epsilon$, and since the magnitude $\epsilon'/\epsilon$ is smaller in any case than a few parts in $10^3$ (as will be discussed in Sec. 4.5), deviations of the phases $\Phi_{+-} \equiv \text{ Arg } \eta_{+-}$ and $\Phi_{00} \equiv \text{ Arg } \eta_{00}$ from the superweak value are expected to be extremely small if CPT invariance is valid. (Parametrizations in which CPT violation is allowed have been discussed, for example, in several reviews$^3$)

### 2.3. Recent developments

A recent experiment at Fermilab$^4$ has measured the phase $\Phi_{+-}$ to be very close to the “superweak” value: $\Phi_{+-} = (43.35 \pm 0.70 \pm 0.79)^\circ$. The difference $\Delta \Phi \equiv \Phi_{+-} - \Phi_{00}$ is measured even more precisely, since the phase of the $K_S$ regeneration amplitude cancels: $\Delta \Phi = (0.67 \pm 0.85 \pm 1.1)^\circ$. This is in marked contrast to the situation several years ago, when $\Delta \Phi$ appeared to be about two standard deviations away from zero with an error of about six degrees.

Another indication of the consistency of $\Phi_{+-}$ with expectations is the quantity $2 \text{ Re } \epsilon \equiv (3.30 \pm 0.12) \times 10^{-3}$ measured via the charge asymmetry in $K_L \rightarrow \pi\ell\nu$ decays$^4$. Using the new value of $\Phi_{+-}$, and neglecting the small contribution of $\epsilon'$, we obtain from the measured values of $|\epsilon|$ and $\Phi_{+-}$ the value $2 \text{ Re } \epsilon = (3.29 \pm 0.07) \times 10^{-3}$, in excellent agreement with that measured directly.

These results, together with the inconclusive nature of the search for $\epsilon' \neq 0$ to be mentioned in Sec. 4.5, leave the parameter $\epsilon$ as the single manifestation of CP violation for which we have hard evidence so far. CPT appears for the moment to be a valid symmetry. We now discuss a possible reason for $\epsilon \neq 0$. 
3. CKM Phases

3.1. Candidate theory of CP violation

The box diagrams which mix $K^0 \equiv d\bar{s}$ and $\bar{K}^0 \equiv s\bar{d}$ involve intermediate states of $u, c, t$ quarks and the corresponding charge-changing couplings of $W$ bosons. Phases in these couplings can give rise to a CP-violating mixing term, leading to $\epsilon \neq 0$. Three quark families are needed in order to obtain phases which cannot be rotated away by redefinition of quark fields.

Neutral $B$ mesons also mix with their antiparticles, and since they involve bottom rather than strange quarks, some of the phases in the couplings are different.

3.2. Origin of the CKM matrix

The initial SU(2)$_L \times$ U(1) electroweak Lagrangian, before electroweak symmetry breaking, may be written in flavor-diagonal form as

$$\mathcal{L}_{\text{int}} = -\frac{g}{\sqrt{2}}[U'_{L\mu} W^{(+)\mu} D_L + H.c.]$$

where $U' \equiv (u', c', t')$ and $D' \equiv (d', s', b')$ are column vectors describing weak eigenstates. Here $g$ is the weak SU(2)$_L$ coupling constant, and $\psi_L \equiv (1 - \gamma_5)\psi/2$ is the left-handed projection of the fermion field $\psi = U$ or $D$.

Quark mixings arise because mass terms in the Lagrangian are permitted to connect weak eigenstates with one another. Thus, the matrices $\mathcal{M}_U, D$ in

$$\mathcal{L}_m = -[U_{R}^\dagger \mathcal{M}_U U'_L + \bar{D}_{R}^\dagger \mathcal{M}_D D'_L + H.c.]$$

may contain off-diagonal terms. One may diagonalize these matrices by separate unitary transformations on left-handed and right-handed quark fields:

$$R^+_Q \mathcal{M}_Q L_Q = L^+_Q \mathcal{M}_Q^+ R_Q = \Lambda_Q$$

where

$$Q'_L = L_Q Q_L; \quad Q'_R = R_Q Q_R \quad (Q = U, D)$$

Using the relation between weak eigenstates and mass eigenstates: $U'_L = L_U U_L, D'_L = L_D D_L$, we find

$$\mathcal{L}_{\text{int}} = -\frac{g}{\sqrt{2}}[U_L^\dagger \Lambda W V D_L + H.c.]$$

where $U \equiv (u, c, t)$ and $D \equiv (d, s, b)$ are the mass eigenstates, and $V \equiv L^+_U L_D$. The matrix $V$ is just the Cabibbo-Kobayashi-Maskawa matrix. By construction, it is unitary: $V^+ V = V V^+ = 1$. It carries no information about $R_U$ or $R_D$. More information would be forthcoming from interactions sensitive to right-handed quarks or from a genuine theory of quark masses.
3.3. Parameters and their values

The CKM matrix for three families of quarks and leptons will have four independent parameters no matter how it is represented. In a parametrization in which the rows of the CKM matrix are labelled by $u$, $c$, $t$ and the columns by $d$, $s$, $b$, we may write

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}. \quad (9)$$

Note the phases in the elements $V_{ub}$ and $V_{td}$. These phases allow the standard $V - A$ interaction to generate CP violation as a higher-order weak effect.

The parameters of the CKM matrix are measured in various ways, some of which are described in more detail elsewhere at this conference.

1. The parameter $\lambda$ is measured by a comparison of strange particle decays with muon decay and nuclear beta decay, leading to $\lambda \approx \sin \theta \approx 0.22$, where $\theta$ is just the Cabibbo angle.

2. The dominant decays of $b$-flavored hadrons occur via the element $V_{cb} = A\lambda^2$. The lifetimes of these hadrons and their semileptonic branching ratios then lead to estimates in the range $A = 0.7 - 0.9$.

3. The decays of $b$-flavored hadrons to charmless final states allow one to measure the magnitude of the element $V_{ub}$ and thus to conclude that $\sqrt{\rho^2 + \eta^2} = 0.2 - 0.5$.

4. The least certain quantity is the phase of $V_{ub}$: $\text{Arg}(V_{ub}^*) = \arctan(\eta/\rho)$. We shall mention ways in which information on this quantity may be improved, in part by indirect information associated with contributions of higher-order diagrams involving the top quark.

The unitarity of $V$ and the fact that $V_{ud}$ and $V_{tb}$ are very close to 1 allows us to write $V_{ub}^* + V_{td} \approx A\lambda^3$, or, dividing by a common factor of $A\lambda^3$,

$$\rho + i\eta + (1 - \rho - i\eta) = 1. \quad (10)$$

The point $(\rho, \eta)$ thus describes in the complex plane one vertex of a triangle whose other two vertices are $(0, 0)$ and $(0, 1)$. This triangle and conventional definitions of its angles are depicted in Fig. 1.

3.4. Indirect information

Indirect information on the CKM matrix comes from $B^0 - \bar{B}^0$ mixing and CP-violating $K^0 - \bar{K}^0$ mixing, through the contributions of box diagrams involving two
Figure 1: The unitarity triangle. (a) Relation obeyed by CKM elements; (b) relation obeyed by (CKM elements)/\lambda^3

Figure 2: Types of allowed regions in (\rho, \eta) plane arising from B – \bar{B} mixing (dashes), CP-violating K – \bar{K} mixing (solid), and |V_{ub}/V_{cb}| (dots)

charged W bosons and two quarks of charge 2/3 (u, c, t) on the intermediate lines. Evidence for the top quark with a mass of \( m_t = 174 \pm 10 ^{+13}_{-12} \) GeV/c^2 has recently been reported\(^{21}\), reducing the errors associated with these box diagrams.

The original evidence for \( B^0 – \bar{B}^0 \) mixing came from the presence of “wrong-sign” leptons in \( B \) meson semileptonic decays.\(^{22}\) The splitting \( \Delta m_B \) between mass eigenstates is proportional to \( f_B^2 m_t^2 |V_{td}|^2 \) times a slowly varying function of \( m_t \). Here \( f_B \) is the \( B \) meson decay constant. The contributions of lighter quarks in the box diagrams, while necessary to cut off the high-energy behavior of the loop integrals, are numerically insignificant.

The CKM element \( |V_{td}| \) is proportional to \( |1 – \rho – i\eta| \). Thus, exact knowledge of \( \Delta m_B \), \( f_B \) and \( m_t \) would specify a circular arc in the (\rho, \eta) plane with center (1,0). Errors on all these quantities spread this arc out into a band, as illustrated schematically by the dashed lines in Fig. 2.

Present averages\(^{23}\) give \( (\Delta m_B/\Gamma_B) = 0.71 \pm 0.07 \). This large value is good news for the prospect of observing CP-violating asymmetries in \( B^0 \) decays.

Similar box diagrams govern CP-violating \( K^0 – \bar{K}^0 \) mixing. Here the dominant contribution to the imaginary part of the mass matrix element \( M_{12} \) discussed in Sec. 2, which gives rise to the parameter \( \epsilon \), is proportional to \( f_K^2 m_t^2 \text{ Im} (V_{td}^2) \) times a slowly varying function of \( m_t \). Charmed quarks also provide a small contribution.
Figure 3: Contours of 68% (inner curve) and 90% (outer curve) confidence levels for regions in the $(\rho, \eta)$ plane. Dotted semicircles denote central value and $\pm 1\sigma$ limits implied by $|V_{ub}/V_{cb}| = 0.08 \pm 0.03$. Plotted point corresponds to minimum $\chi^2 = 0.17$, while (dashed, solid) curves correspond to $\Delta \chi^2 = (2.3, 4.6)$.

The kaon decay constant is known: $f_K = 160$ MeV. The imaginary part of $V_{td}$ is proportional to $\eta(1 - \rho)$. Knowledge of $\epsilon$ thus specifies a hyperbola in the $(\rho, \eta)$ plane with focus at $(1, 0)$, which is spread out into a band (the solid lines in Fig. 2) because of uncertainties in hadronic matrix elements.

3.5. Allowed $(\rho, \eta)$ region

Information on $|V_{ub}/V_{cb}|$ specifies a circular band in the $(\rho, \eta)$ plane, as depicted by the dotted lines in Fig. 2. When this constraint is added to those mentioned in the previous subsection, one obtains the potato-shaped region shown in Fig. 3. Here we have taken $m_t = 174 \pm 17$ GeV/$c^2$, $f_B = 180 \pm 30$ MeV, $(\rho^2 + \eta^2)^{1/2} = 0.36 \pm 0.14$ (corresponding to $|V_{ub}/V_{cb}| = 0.08 \pm 0.03$), and $A = 0.79 \pm 0.09$ (corresponding to $V_{cb} = 0.038 \pm 0.005$). A parameter known as $B_K$ describes the degree to which the box diagrams dominate the $CP$-violating $K^0 - \bar{K}^0$ mixing. We take $B_K = 0.8 \pm 0.2$, and set the corresponding value for $B$ mesons equal to 1. A QCD correction to the $B^0 - \bar{B}^0$ mixing amplitude has been taken to be $\eta_{QCD} = 0.6 \pm 0.1$; this is perhaps a generous error in view of the existence of a more precise estimate of this quantity. Other parameters and fitting methods are as discussed in more extensive treatments elsewhere. Several parallel analyses reach qualitatively similar conclusions.

The best fit corresponds to $\rho \simeq 0$, $\eta \simeq 0.36$, while at 90% confidence level the
allowed ranges are:
\[
\eta \simeq 0.3 : \quad -0.4 \leq \rho \leq 0.4 ;
\]
\[
\rho \simeq 0 : \quad \eta \simeq 0.3 \times 2^{\pm 1} .
\]

The only evidence for \( \eta \neq 0 \) comes from CP violation in the kaon system. We see from Fig. 3 that an acceptable description of this phenomenon can be obtained with a wide range of CKM parameters. In the next two sections we mention some tests that could confirm the picture.

4. Improved tests

A few ways to improve information about CKM matrix elements are listed below. Others (e.g., better measurements of \( |V_{cb}| \) or \( |V_{ub}| \)) are mentioned elsewhere in this conference or in more extensive reviews.

4.1. Decay constant information

If \( f_B \) were better known, the indeterminacy in the \((\rho, \eta)\) plane would be reduced considerably. We show in Fig. 4 the variation in \( \chi^2 \) for the fit described in the previous section when \( f_B \) is taken to have a fixed value. An acceptable fit is obtained for a wide range of values, with \( \chi^2 = 0 \) for \( f_B = 153 \) and 187 MeV.

The reason for the flat behavior of \( \chi^2 \) with \( f_B \) is illustrated in Fig. 5. The dashed line, labeled by values of \( f_B \), depicts the \((\rho, \eta)\) value for the solution with minimum \( \chi^2 \) at each \( f_B \). The product \(|1 - \rho - i\eta|f_B\) is constrained to be a constant by \( B^0 - \bar{B}^0 \) mixing. The product \( \eta(1 - \rho) \) is constrained to be constant by the value of \( \epsilon \). The locus of solutions to these two conditions lies approximately tangent to the circular arc associated with the constraint on \( |V_{ub}/V_{cb}| \) for a wide range of values of \( f_B \).

The uncertainty in \( f_B \) thus becomes a major source of uncertainty in \( \rho \), which will not improve much with better information on \( |V_{ub}/V_{cb}| \). Fortunately, several estimates of \( f_B \) are available, and their reliability should improve.

Lattice gauge theories have attempted to evaluate decay constants for \( D \) and \( B \) mesons. A representative set is

\[
\begin{align*}
    f_B &= 187 \pm 10 \pm 34 \pm 15 \text{ MeV} , \\
    f_{B_s} &= 207 \pm 9 \pm 34 \pm 22 \text{ MeV} , \\
    f_D &= 208 \pm 9 \pm 35 \pm 12 \text{ MeV} , \\
    f_{D_s} &= 230 \pm 7 \pm 30 \pm 18 \text{ MeV} ,
\end{align*}
\]

where the first errors are statistical, the second are associated with fitting and lattice constant, and the third arise from scaling from the static \( (m_Q = \infty) \) limit. The spread between these and some other lattice estimates is larger than the errors quoted above, however.
Figure 4: Variation of $\chi^2$ in a fit to CKM parameters as a function of $f_B$.

Figure 5: Locus of points in $(\rho, \eta)$ corresponding to minimum $\chi^2$ for fixed values of $f_B$. Circular arcs depict central value and $\pm 1\sigma$ errors for $|V_{ub}/V_{cb}|$. Solid dots denote points with $\chi^2 = 0$. 
**Direct measurements** are available so far only for the $D_s$ decay constant. The WA75 collaboration\textsuperscript{32} has seen $6 - 7$ $D 	o \mu \nu$ events and conclude that $f_{D_s} = 232 \pm 69$ MeV. The CLEO Collaboration\textsuperscript{33} has a much larger statistical sample; the main errors arise from background subtraction and overall normalization (which relies on the $D_s \to \phi \pi$ branching ratio). Using several methods to estimate this branching ratio, Muheim and Stone\textsuperscript{44} estimate $f_{D_s} = 315 \pm 45$ MeV. We average this with the WA75 value to obtain $f_{D_s} = 289 \pm 38$ MeV.

**Quark models** can provide estimates of decay constants and their ratios. In a non-relativistic model,\textsuperscript{35} the decay constant $f_M$ of a heavy meson $M = Q\bar{q}$ with mass $M_M$ is related to the square of the $Q\bar{q}$ wave function at the origin by $f_M^2 = 12|\Psi(0)|^2/M_M$. The ratios of squares of wave functions can be estimated from strong hyperfine splittings between vector and pseudoscalar states, $\Delta M_{hs} \propto |\Psi(0)|^2/m_Q m_q$. The equality of the $D_s^* - D_s$ and $D^* - D$ splittings then suggests that

$$f_D/f_{D_s} \simeq (m_d/m_s)^{1/2} \simeq 0.8 \simeq f_B/f_{B_s},$$

where we have assumed that similar dynamics govern the light quarks bound to charmed and $b$ quarks. Using our average for $f_{D_s}$, we find $f_D = (231 \pm 31)$ MeV. This is to be compared with the Mark III upper limit\textsuperscript{36} $f_D < 290$ MeV (90% c.l.).

An absolute estimate of $|\Psi(0)|^2$ can be obtained using electromagnetic hyperfine splittings,\textsuperscript{37} which are probed by comparing isospin splittings in vector and pseudoscalar mesons. Before corrections of order $1/m_Q$, the values $f_D^{(0)} = (290 \pm 15)$ MeV, $f_B^{(0)} = (177 \pm 9)$ MeV were obtained. With $f_M = f_M^{(0)}(1-\Delta/m_M)$ ($M = D, B$), we use our value of $f_D$ to estimate $\Delta/M_D = 0.20 \pm 0.11$, $\Delta/M_B = 0.07 \pm 0.04$, and hence $f_B = f_B^{(0)}(1-\Delta/m_B) = 164 \pm 11$ MeV. Applying a QCD correction\textsuperscript{38} of 1.10 to the ratio $f_B/f_D$, we finally estimate $f_B = (180 \pm 12)$ MeV. [This is the basis of the value taken in the previous Section, where we inflated the error arbitrarily.] We also obtain $f_{B_s} = (225 \pm 15)$ MeV from the ratio based on the quark model.

### 4.2. Rates and Ratios

The partial width $\Gamma(B \to \ell \nu)$ is proportional to $f_B^2 |V_{ub}|^2$. The expected branching ratios are about $(1/2) \times 10^{-4}$ for $\tau \nu$ and $2 \times 10^{-7}$ for $\mu \nu$. Another interesting ratio is $\Gamma(B \to \rho \gamma)/\Gamma(B \to K^* \gamma)$, which, aside from small phase space corrections, should just be $|V_{td}/V_{ts}|^2 \simeq 1/20$.

### 4.3. The $K^+ \to \pi^+ \nu \bar{\nu}$ rate

The decay $K^+ \to \pi^+ \nu \bar{\nu}$ is governed by loop diagrams involving the cooperation of charmed and top quark contributions. The branching ratio will provide useful information on $\rho$.\textsuperscript{29} The ranges of $(\rho, \eta)$ favored in the fit of Fig. 3 imply that for $m_t = (160, 175, 190)$ GeV$/c^2$ the 90% c.l. limits of the branching ratio (in units of $10^{-10}$) are $(0.6$ to $1.6, 0.7$ to $1.9, 0.7$ to $2.2)$. Thus, the favored value is slightly above $10^{-10}$, give or take a factor of 2. A low value within this range signifies
\[ \rho > 0, \text{ while a high value signifies } \rho < 0. \] The present published upper limit is \( B(K^+ \to \pi^+ \nu \bar{\nu}) < 5 \times 10^{-9} \) (90% c.l.), with a recent unpublished improvement to \( 3 \times 10^{-9} \) (90% c.l.).

4.4. Other \( K_L \to \pi^0 \ell \bar{\ell} \) decays

The decay \( K_L \to \pi^0 e^+ e^- \) is expected to be dominated by CP-violating contributions, though the possibility of CP-conserving contributions through a two-photon intermediate state could be laid to rest by more detailed studies of the decay \( K_L \to \pi^0 \gamma \gamma \). Two types of CP-violating contributions are expected: “indirect,” via the CP-positive component \( K_1 \) component of \( K_L = K_1 + \epsilon K_2 \), and “direct,” whose presence would be a detailed verification of the CKM theory of CP violation.

The indirect contribution is expected to lead to a branching ratio \( B^{\text{in}} \approx 6 \times 10^{-12} \), though one calculation finds it an order of magnitude larger. The phase of the indirect contribution is expected to be that of \( \epsilon \) (i.e., about \( 45^\circ \)) modulo \( \pi \). The direct contribution should be proportional to \( i\eta \), and should be comparable in magnitude to the indirect contribution in most estimates. One potential background is the process \( K_L \to \gamma_1 e^+ e^- \), where the positron or electron radiates a photon \( (\gamma_2) \). If \( m(\gamma_1 \gamma_2) \) is too close to \( m_{\pi^0} \), this process can be confused with the signal.

The present 90% c.l. upper limit to \( B(K_L \to \pi^0 e^+ e^-) \) is \( 1.8 \times 10^{-9} \), where results from several experiments have been combined.

The decay \( K_L \to \pi^0 \mu^+ \mu^- \) should have less background than \( K_L \to \pi^0 e^+ e^- \) from photons radiated by the charged leptons, and should have a comparable rate (aside from phase space differences). The present 90% c.l. upper limit is \( 5.1 \times 10^{-9} \).

The decay \( K_L \to \pi^0 \nu \bar{\nu} \) should have a branching ratio of about \( 2 \times 10^{-10} \eta^2 \) for \( m_t = 175 \) GeV. It should have only a very small indirect contribution, and would be incontrovertible evidence for the CKM theory. At present, experimental bounds are \( B(K_L \to \pi^0 \nu \bar{\nu}) < 5.8 \times 10^{-5} \) (90% c.l., summed over neutrino species).

4.5. The ratio \( \epsilon'/\epsilon \) for kaons

The observation of a nonzero value of \( \epsilon'/\epsilon \) (Section 2.2) has long been viewed as one of the most promising ways to disprove a “superweak” theory of this effect. The latest estimates are equivalent (for a top mass of about 170 GeV/c^2) to \( [\epsilon'/\epsilon]_{\text{kaons}} = (6 \pm 3) \times 10^{-4} \eta \), with an additional factor of 2 uncertainty associated with hadronic matrix elements. The Fermilab E731 Collaboration measures \( \epsilon'/\epsilon = (7.4 \pm 6) \times 10^{-4} \), leading to no restrictions on \( \eta \) in comparison with the range \( (0.2 \text{ to } 0.6) \) we have already specified. The CERN NA31 Collaboration finds \( \epsilon'/\epsilon = (23 \pm 7) \times 10^{-4} \), which is higher than theoretical expectations. Both groups are preparing new experiments, for which results should be available around 1996.
Table 1: Dependence of mixing parameter $x_s$ on top quark mass and $B_s$ decay constant.

| $m_t$ (GeV/$c^2$) | 157  | 174  | 191  |
|-------------------|------|------|------|
| $f_{B_s}$ (MeV)   |      |      |      |
| 150               | 7.6  | 8.9  | 10.2 |
| 200               | 13.5 | 15.8 | 18.2 |
| 250               | 21.1 | 24.7 | 28.4 |

5. Detailed $B$ studies

The properties of $B$ mesons are particularly appropriate for testing the CKM theory of CP violation, since the third family of quarks is essential to this theory. Indeed, many aspects of $B$ physics provide relevant information, including $B_s - \bar{B}_s$ mixing, CP violation in neutral and charged $B$ decays, and the study of relations among decay rates.

5.1. $B_s - \bar{B}_s$ mixing

The same type of box diagrams which lead to $K^0 - \bar{K}^0$ and $B^0 - \bar{B}^0$ mixing also mix strange $B$ mesons with their antiparticles. One expects $(\Delta m)|_{B_s}/(\Delta m)|_{B_d} = (f_{B_s}/f_{B_d})^2(B_{B_s}/B_{B_d})|V_{ts}/V_{td}|^2$, which should be a very large number (of order 20 or more). Thus, strange $B$’s should undergo many particle-antiparticle oscillations before decaying.

The main uncertainty in an estimate of $x_s \equiv (\Delta m/\Gamma)_{B_s}$ is associated with $f_{B_s}$. The CKM elements $V_{ts} \simeq -0.04$ and $V_{tb} \simeq 1$ which govern the dominant (top quark) contribution to the mixing are known reasonably well. We show in Table 1 the dependence of $x_s$ on $f_{B_s}$ and $m_t$. To measure $x_s$, one must study the time-dependence of decays to specific final states and their charge-conjugates with resolution equal to a small fraction of the $B_s$ lifetime (about 1.5 ps).

5.2. CP violation in $B$ decays

Soon after the discovery of the $\Upsilon$ states it was realized that CP-violating phenomena in decays of $B$ mesons were expected to be observable and informative.

Decays of neutral $B$ mesons to CP eigenstates $f$ can exhibit rate asymmetries (or time-dependent asymmetries) as a result of the interference of the direct process $B^0 \to f$ and the two-step process $B^0 \to \bar{B}^0 \to f$ involving mixing.

Decays to CP non-eigenstates can exhibit rate asymmetries only if there are two different weak decay amplitudes and two different strong phase shifts associated with them. Comparing

$$\Gamma \equiv \Gamma(B^0 \to f) = |a_1 e^{i(\phi_1 + \delta_1)} + a_2 e^{i(\phi_2 + \delta_2)}|^2$$

(14)
with
\[ \Gamma \equiv \Gamma(B^0 \rightarrow f) = |a_1 e^{i(-\phi_1 + \delta_1)} + a_2 e^{i(-\phi_2 + \delta_2)}|^2 \]
we notice that only the weak phases \( \phi_i \) change sign under CP inversion, not the strong phases \( \delta_i \). Defining \( \phi \equiv \phi_1 - \phi_2, \delta \equiv \delta_1 - \delta_2 \), we find
\[ \Gamma - \bar{\Gamma} \propto 2a_1 a_2 \sin \phi \sin \delta, \]
so both \( \phi \) and \( \delta \) must be nonzero in order to see a rate difference.

5.3. Decays involving neutral B’s

Asymmetries decays of neutral B mesons to CP eigenstates can provide direct information about the angles in the unitarity triangle of Fig. 1. We may define a time-integrated rate asymmetry \( A(f) \) as
\[ A(f) \equiv \frac{\Gamma(B^0_{t=0} \rightarrow f) - \Gamma(\bar{B}^0_{t=0} \rightarrow f)}{\Gamma(B^0_{t=0} \rightarrow f) + \Gamma(\bar{B}^0_{t=0} \rightarrow f)}. \]
The angles \( \beta \) and \( \alpha \) in Fig. 1 are related to the asymmetries in decays to \( J/\psi K_S \) and \( \pi^+ \pi^- \) final states:
\[ A(J/\psi K_S) = -\frac{x_d}{1 + x_d^2} \sin 2\beta, \]
\[ A(\pi^+ \pi^-) = -\frac{x_d}{1 + x_d^2} \sin 2\alpha, \]
where \( x_d \equiv (\Delta m/\Gamma)|_{B^0} \), and we have neglected lifetime differences between eigenstates. The contours of Fig. 3 imply that the asymmetry \( A(J/\psi K_S) \) should be between \(-0.1\) and its most negative value of \( x_d^2/1 + x_d^2 = -0.47 \). If it lay outside these bounds, it could immediately disprove the CKM explanation of CP violation in the neutral kaon system. The asymmetry \( A(\pi^+ \pi^-) \) can take on any value between \(-0.47\) and \(+0.47\). It would thus provide very helpful information on CKM parameters.

5.4. Tagging of neutral B decays

In the study of decays of neutral B mesons to CP eigenstates, one must know whether a \( B^0 \) or \( \bar{B}^0 \) was produced at \( t = 0 \). One suggestion is to correlate the neutral B meson with a charged pion, as in the decay of a higher-lying resonance. This tagging method has been used to tag neutral charmed mesons, where the decays \( D^{*+} \rightarrow D^0 \pi^+ \) and \( D^{*-} \rightarrow \bar{D}^0 \pi^- \) are kinematically allowed, in order to look for mixing or to compare decays involving the highly suppressed subprocess \( c \rightarrow du\bar{s} \) with those involving the favored subprocess \( c \rightarrow sud \).

The usefulness of the method for B mesons can be checked by learning the degree to which a correlation exists between a charged pion and a \( B^0 \) decay to states of
identified flavor such as \( J/\psi K^* \) (with \( K^* \rightarrow K^+\pi^- \)) or \( D^-\pi^+ \). Under normal circumstances the \( B \) mesons are produced in an isospin-independent manner and one can study these correlations using charged \( B \) mesons as well.

The correlation is easily visualized with the help of quark diagrams. By convention (the same as for kaons), a neutral \( B \) meson containing an initially produced \( \bar{b} \) is a \( B^0 \). It also contains a \( d \) quark. The next charged pion down the fragmentation chain must contain a \( \bar{d} \), and hence must be a \( \pi^+ \). Similarly, a \( \bar{B}^0 \) will be correlated with a \( \pi^- \).

The same conclusion can be drawn by noting that a \( B^0 \) can resonate with a positive pion to form an excited \( B^{*+} \), which we shall call \( B^{**+} \) (to distinguish it from the \( B^* \), lying less than 50 MeV/\( c^2 \) above the \( B \)). Similarly, a \( \bar{B}^0 \) can resonate with a negative pion to form a \( B^{**-} \). The combinations \( B^0\pi^- \) and \( B^0\pi^+ \) are exotic, i.e., they cannot be formed as quark-antiquark states. No evidence for exotic resonances exists.

The lightest states which can decay to \( B\pi \) and/or \( B^*\pi \) are P-wave resonances of a \( b \) quark and a \( \bar{u} \) or \( \bar{d} \). The expectations for masses of these states, based on extrapolation from the known \( D^{**} \) resonances, are summarized in Table 2.

The known \( D^{**} \) resonances are a \( 2^+ \) state around 2460 MeV/\( c^2 \), decaying to \( D\pi \) and \( D^*\pi \), and a \( 1^+ \) state around 2420 MeV/\( c^2 \), decaying to \( D^*\pi \). These states are relatively narrow, probably because they decay via a D-wave. In addition, there are expected to be much broader (and probably lower) \( D^{**} \) resonances: a \( 1^+ \) state decaying to \( D^*\pi \) and a \( 0^+ \) state decaying to \( D\pi \), both via S-waves.

5.5. Decays of \( B \)'s to pairs of pseudoscalars

I would like to report on some new work in collaboration with M. Gronau, O. Hernández, and D. London. The decays \( B \rightarrow (\pi\pi, \pi K, K\bar{K}) \) are a rich source of information on both weak (CKM) and strong phases, if we are willing to use flavor SU(3) symmetry.

The decays \( B \rightarrow \pi\pi \) are governed by transitions \( b \rightarrow dq\bar{q} \ (q = u, d, \ldots) \) with \( \Delta I = 1/2 \) and \( \Delta I = 3/2 \), leading respectively to final states with \( I = 0 \) and \( I = 2 \). Since there is a single amplitude for each final isospin but three different charge states in the decays, the amplitudes obey a triangle relation: \( A(\pi^+\pi^-) \) -
\[ \sqrt{2}A(\pi^0\pi^0) = \sqrt{2}A(\pi^+\pi^0) \]. The triangle may be compared with that for the charge-conjugate processes and combined with information on time-dependent \( B \to \pi^+\pi^- \) decays to obtain information on weak phases.\[ \text{63} \]

The decays \( B \to \pi K \) are governed by transitions \( b \to sq\bar{q} \) \((q = u, d, \ldots)\) with \( \Delta I = 0 \) and \( \Delta I = 1 \). The \( I = 1/2 \) final state can be reached by both \( \Delta I = 0 \) and \( \Delta I = 1 \) transitions, while only \( \Delta I = 1 \) contributes to the \( I = 3/2 \) final state. Consequently, there are three independent amplitudes for four decays, and one quadrangle relation \( A(\pi^+K^0) + \sqrt{2}A(\pi^0K^+) = A(\pi^-K^+) + \sqrt{2}A(\pi^0K^0) \). As in the \( \pi\pi \) case, this relation may be compared with the charge-conjugate one and the time-dependence of decays to CP eigenstates (in this case \( \pi^0 K_S \)) studied to obtain CKM phase information.\[ \text{58} \]

We have re-examined SU(3) analyses of the decays \( B \to PP \) \((P = \text{light pseudoscalar})\). They imply a number of useful relations among \( \pi\pi \), \( \pi K \), and \( K\bar{K} \) decays, among which is one relating \( B^+ \) amplitudes alone:

\[ A(\pi^+K^0) + \sqrt{2}A(\pi^0K^+) = r_u\sqrt{2}A(\pi^+\pi^0) \quad . \tag{20} \]

Here \( r_u \equiv (f_K/f_\pi)|V_{us}/V_{ud}| \). This expression relates one side of the \( \pi\pi \) amplitude triangle to one of the diagonals of the \( \pi K \) amplitude quadrangle, and thus reduces the quadrangle effectively to two triangles, simplifying previous analyses.\[ \text{63} \] Moreover, since one expects the \( \pi^+ K^0 \) amplitude to be dominated by a penguin diagram (with expected weak phase \( \pi \)) and the \( \pi^+ \pi^0 \) amplitude to have the phase \( \gamma = \text{Arg} V_{ub}^* \), the comparison of this last relation and the corresponding one for charge-conjugate decays can provide information on the weak phase \( \gamma \).

In Fig. 6 we compare the amplitude triangles for \( B^+ \) and \( B^- \) decays. The angle between the sides corresponding to \( B^+ \to \pi^+\pi^0 \) and \( B^- \to \pi^-\pi^0 \) is \( 2\gamma \). Two possible orientations for the triangles are shown.

The amplitude \( A(\pi^0K^+) \) which is the sum of “tree” and penguin graph contributions can be expressed as:

\[ \sqrt{2}A(\pi^0K^+) = Ae^{i\gamma}e^{i\delta_3} + Be^{i\delta_P} = e^{i\delta_P}(Ae^{i\gamma}e^{i\delta} + B) \quad , \tag{21} \]

where \( \delta_3 \) is the strong \( I = 3/2 \) phase, \( \delta_P \) is the strong penguin phase, and \( \delta \equiv \delta_3 - \delta_P \). In the corresponding expression for \( A(\pi^0K^-) \), only the sign of \( \gamma \) is changed. The \( \pi^0K^\pm \) decay rates are then

\[ \Gamma(\pi^0 K^\pm) = (1/2)[A^2 + B^2 + 2AB \cos(\delta \pm \gamma)] \quad . \tag{22} \]

The sum and difference of these rates are

\[ S \equiv \Gamma(\pi^0 K^+) + \Gamma(\pi^0 K^-) = A^2 + B^2 + 2AB \cos \delta \cos \gamma \quad , \tag{23} \]

\[ D \equiv \Gamma(\pi^0 K^+) - \Gamma(\pi^0 K^-) = 2AB \sin \delta \sin \gamma \quad . \tag{24} \]

The CP-violating rate difference \( D \) is probably very small as a result of the likely smallness of the phase difference \( \delta \).
Figure 6: Amplitude triangles illustrating the extraction of the weak phase $\gamma$ from charged $B$ decays to $\pi\pi$ and $\pi K$. 
Let us take as an example $|A/B| = 1/3$, $\delta = 0$, and $\cos \gamma \simeq 0$. Expressing $\cos \gamma = (S - A^2 - B^2)/2AB$, we find that in order to measure $\gamma$ to $10^\circ$ one needs a sample consisting of about 100 events in the channel $\pi^0K^\pm$ corresponding to $S$.

Further relations can be obtained by comparing the amplitude triangles involving both charged and neutral $B$ decays to $\pi K$. By looking at the amplitude triangles for these decays and their charge conjugates, one can sort out a number of weak and strong phases.

Some combination of the decays $B^0 \rightarrow \pi^+\pi^-$ and $B^0 \rightarrow \pi^-K^+$ has already been observed. The sum of these two modes is nonzero at better than the $4\sigma$ level, corresponding to a combined branching ratio of $2 \times 10^{-5}$. The most likely solution is that there are about 7 events in each channel, each with a branching ratio of about $10^{-5}$. Since the $B^0 \rightarrow \pi^+\pi^-$ decay is expected to be dominated by a “tree” subprocess $b \rightarrow u\bar{u}d$ while $B^0 \rightarrow \pi^-K^+$ should be dominated by a penguin amplitude $b \rightarrow s+\text{gluon}$, there is hope that these amplitudes should be of comparable size. Taking account of the likely size of the factor $\tilde{r}_u$ then led us to the estimate $|A/B| = 1/3$ mentioned above.

Other $90\%$ c.l. upper limits are $B(B^0 \rightarrow \pi^0\pi^0) < 2.7 \times 10^{-5}$, $B(B^+ \rightarrow \pi^+\pi^0) < 4.4 \times 10^{-5}$, and $B(B^+ \rightarrow \pi^0K^+) < 2.6 \times 10^{-5}$. It will be necessary to improve the data sample by about a factor of 100 before the tests mentioned above can be contemplated, but this is within the possibility of planned facilities.

6. Alternative sources of CP violation

6.1. The superweak model

It is possible to explain the nonzero value of $\epsilon$ in the neutral kaon system by means of an ad hoc $\Delta S = 2$ interaction leading directly to CP-violating $K^0 - \bar{K}^0$ mixing. The phase of $\epsilon$ will then automatically be the superweak phase mentioned in Section 2, and one will see no difference between $\eta_\pi$ and $\eta_{K0}$. The only evidence against this possibility so far is the $3\sigma$ observation of nonzero $\epsilon'/\epsilon$ by the CERN NA31 experiment, a result not confirmed by Fermilab E731.

A superweak interaction (of considerably greater strength) could in principle lead to observable CP-violating $B^0 - \bar{B}^0$ mixing. If this were so, one would expect $A(\pi^+\pi^-) = -A(J/\psi K_S)$ as a result of the opposite CP eigenvalues of the two final states. In order for this relation to hold in the standard model, one would need $\eta = (1 - \rho)[\rho/(2 - \rho)]^{1/2}$. Taking account of possible errors in checking that the asymmetries are actually equal and opposite, one concludes that a portion of the allowed region of parameters shown in Fig. 3 could not be distinguished from a superweak theory. The ratio $A(\pi^+\pi^-)/A(J/\psi K_S)$ is informative in a more general context: for example, if it exceeds 1, then $\rho$ must be negative.

If $\epsilon$ arises entirely from a superweak interaction, there is no need for CKM phases, and one will see no “direct” effects in kaon or $B$ decays. There will also be
no neutron or electron electric dipole moments, though such effects also will be well below experimental capabilities in the standard CKM picture.

6.2. Right-handed W’s

If there are new W bosons (“right-handed W’s, or $W_R$) coupling to right-handed fermions, one can obtain CP-violating interactions (for example, via box diagrams involving $W_R$ and the usual left-handed $W_L$). The right-handed W mass scale must be tens of TeV or less in order for a large enough contribution to $\epsilon$ to be generated. In contrast to the situation described in Section 3.2, one can generate CP violation using only two quark families, since redefinitions of quark phases are constrained by the right-handed couplings.

An amusing feature of right-handed W couplings is that their participation (or even dominance) in b quark decays is surprisingly hard to rule out. Some suggestions have been made to test the usual picture of left-handed $b \rightarrow c$ decays using the polarization of $\Lambda_b$ baryons produced in $b$ quark fragmentation.

6.3. Multi-Higgs models

If there is more than one Higgs doublet, complex vacuum expectation values of Higgs fields can lead to CP-violating effects. It appears that in order to explain $\epsilon \neq 0$ in neutral kaon decays by this mechanism, one expects too large a neutron electric dipole moment. The possibility of such effects remains open, however, and the best test for them remains the study of dipole moments. Current models tend to be constrained by the present limits of

$$|d_n| < 1.1 \times 10^{-25} \, e\cdot cm \, (95\% \, c.l.) \quad , \quad |d_e| < 2 \times 10^{-26} \, e\cdot cm \, (95\% \, c.l.) \, .$$

Other CP-violating effects in multi-Higgs-boson models include transverse lepton polarization in $K_{\mu3}$ decays and various asymmetries in charm decays, which we now discuss briefly.

7. Charm decays

The standard model predicts very small CP-violating effects in charmed particle decays. $D^0 - \bar{D}^0$ mixing is expected to be small and uncertain, dominated by long-distance effects. The short-distance contribution to CP-violating mixing should be of order $(m_b/m_t)^2$ times that in neutral kaons, while the lifetime of a neutral D meson is about 0.4 ps in comparison with 52 ns for a neutral kaon. The tree-level decays $c \rightarrow su\bar{d}$, $c \rightarrow du\bar{d}$, $c \rightarrow du\bar{s}$ have zero or negligible weak phases in the standard convention.

For precisely these reasons, CP-violating charmed particle decays are an excellent place to look for new physics. New effects tend to be accompanied with flavor-changing neutral currents, which may or may not be an advantage in specific cases. Experiments are easy to perform and undersubscribed in comparison...
Table 3: Rate asymmetries in charmed meson decays.

| Charmed meson state | Final state | Asymmetry     |
|---------------------|-------------|---------------|
| $D^+$ $K^-K^+\pi^+$ | $-0.031 \pm 0.068$ |
| $D^+$ $\bar{K}^*0K^+$ | $-0.12 \pm 0.13$ |
| $D^+$ $\phi\pi^+$ | $0.066 \pm 0.086$ |
| $D^0$ $K^+K^-$ | $0.024 \pm 0.084$ |

with the many proposed studies of $B$ physics. Information on rate asymmetries $A(f) \equiv \frac{\Gamma(i \to f) - \Gamma(\bar{i} \to \bar{f})}{\Gamma(i \to f) + \Gamma(\bar{i} \to \bar{f})}$ is just now beginning to appear, as illustrated in Table 3.

8. Baryogenesis

The ratio of baryons to photons in our Universe is a few parts in $10^9$. If baryons and antibaryons had been produced in equal numbers, mutual annihilations should have reduced this quantity to a much smaller number, of order a part in $10^{18}$. In 1967 Sakharov proposed three ingredients of any theory which sought to explain the preponderance of baryons over antibaryons in our Universe: (1) violation of C and CP; (2) violation of baryon number, and (3) a period in which the Universe was out of thermal equilibrium. Thus our very existence may owe itself to CP violation. However, no consensus exists on a specific implementation of Sakharov’s suggestion.

A toy model illustrating Sakharov’s idea can be constructed within an SU(5) grand unified theory. The gauge group SU(5) contains “$X$” bosons which can decay both to $uu$ and to $e^+d$. By CPT, the total decay rates of $X$ and $\bar{X}$ must be equal, but CP-violating rate differences $\Gamma(X \to uu) \neq \Gamma(\bar{X} \to \bar{u}\bar{u})$ and $\Gamma(X \to e^+d) \neq \Gamma(\bar{X} \to e^-\bar{d})$ are permitted. This example conserves $B-L$, where $B$ is baryon number (1/3 for quarks) and $L$ is lepton number (1 for electrons).

It was pointed out by ’t Hooft that the electroweak theory contains an anomaly as a result of nonperturbative effects which conserves $B-L$ but violates $B+L$. If a theory leads to $B-L=0$ but $B+L \neq 0$ at some primordial temperature $T$, the anomaly can wipe out any $B+L$ as $T$ sinks below the electroweak scale.

Thus, the toy model mentioned above and many others are unsuitable in practice. Proposed solutions include (1) the generation of baryon number directly at the electroweak scale rather than at a higher temperature, and (2) the generation of nonzero $B-L$ at a high temperature, e.g., through the generation of nonzero lepton number $L$ which is then reprocessed into nonzero baryon number by the ’t Hooft anomaly mechanism. The first scenario, based on standard model CP-violating interactions (as manifested in the CKM matrix), is widely regarded as inadequate to generate the observed baryon asymmetry at the electroweak scale. We illustrate
in Fig. 7 some aspects of the second scenario. The existence of a baryon asymmetry, when combined with information on neutrinos, could provide a window to a new scale of particle physics.

If neutrinos have masses at all, they are much lighter than their charged counterparts or the corresponding leptons. One possibility for the suppression of neutrino masses is the so-called “seesaw” mechanism, by which light neutrinos acquire Majorana masses of order \( m_M = m_D^2/M_M \), where \( m_D \) is a typical Dirac mass and \( M_M \) is a large Majorana mass acquired by right-handed neutrinos. Such Majorana masses change lepton number by two units and therefore are ideal for generating a lepton asymmetry if Sakharov’s other two conditions are met.

The question of baryogenesis is thus shifted onto the leptons: Do neutrinos indeed have masses? If so, what is their “CKM matrix”? Do the properties of heavy Majorana right-handed neutrinos allow any new and interesting natural mechanisms for violating CP at the same scale where lepton number is violated? Majorana masses for right-handed neutrinos naturally violate left-right symmetry and could
be closely connected with the violation of $P$ and $C$ in the weak interactions.

An open question in this scenario, besides the precise form of CP violation at the lepton-number-violating scale, is how this CP violation gets communicated to the lower mass scale at which we see CKM phases. Presumably this occurs through higher-dimension operators which imitate the effect of Higgs boson couplings to quarks and leptons.

9. The strong CP problem

We did not have time to present this material orally, and so will be very brief in the written version. There are fine reviews elsewhere.

As a result of nonperturbative effects, the QCD Lagrangian acquires an added CP-violating term $g^2 \bar{\theta} F_{\mu\nu} \tilde{F}^{\mu\nu} / 32\pi^2$, where $\bar{\theta} = \theta + \text{Arg} \det M$, $\theta$ is a term describing properties of the QCD vacuum, and $M$ is the quark mass matrix. The limit on the observed neutron electric dipole moment, together with the estimate $d_n \sim 10^{-16} e cm$, implies that $\theta \leq 10^{-9}$, which looks very much like zero. How can one understand this? Several proposals exist.

9.1. Vanishing $m_u$

If one quark mass vanishes (the most likely candidate being $m_u$), one can rotate away any effects of $\bar{\theta}$. However, it is generally though not universally felt that this bends the constraints of chiral symmetry beyond plausible limits. My own guess is that light-quark masses are in the ratios $u : d : s = 3 : 5 : 100$.

9.2. Axion

One can introduce a continuous $U(1)$ global symmetry such that $\bar{\theta}$ becomes a dynamical variable which relaxes to zero as a result of new interactions. The spontaneous breaking of this symmetry then leads to a pseudo-Nambu-Goldstone boson, the axion, for which searches may be performed in many ways. My favorite is via the Primakoff effect, in which axions in the halo of our galaxy interact with a static man-made strong magnetic field to produce photons with frequency equal to the axion mass (up to Doppler shifts). These photons can be detected in resonant cavities. Present searches would have to be improved by about a factor of 100 to detect axions playing a significant role in the mass of the galaxy.

9.3. Boundary conditions

It has been proposed that one consider not the $\theta$-vacuum, but an incoherent mixture consisting of half $\theta$ and half $-\theta$, in the manner of a sum over initial spins of an unpolarized particle. The experimental consequences of this proposal are still being worked out.
10. Summary

The observed CP violation in the neutral kaon system has been successfully parametrized in terms of the Cabibbo-Kobayashi-Maskawa (CKM) matrix. The problem has been shifted to one of understanding the magnitudes and phases of CKM elements. Even before this more ambitious question is addressed, however, one seeks independent tests of the CKM picture of CP violation. Rare $K$ decays and $B$ decays will provide many such tests.

Alternative (non-CKM) theories of CP violation are much more encouraging for some CP-violating quantities like the neutron electric dipole moment or effects in charmed particle decays. However, most of these alternative theories do not predict observable direct CP-violating effects in $K$ or $B$ decays.

No real understanding exists yet of baryogenesis or of the strong CP problem. Fortunately, there exist many possibilities for experiments bearing on these questions, including searches for neutrino masses and for axions.

The CKM picture suggests that we may understand CP violation better when the pattern of fermion masses itself is understood. As an example, why is the top quark heavier than all the other quarks and leptons, or why are the others so much lighter than the top? The observation of the top quark has finally thrust this problem in our faces, and perhaps we will figure out the answer some day.

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