WORKSHOP SUMMARY*

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Abstract

Recent progress in understanding the physics of B mesons and of CP violation, as presented to this Workshop, is put in historical perspective and summarized.
1 Introduction

In the middle of the last century it was realized that neutral mesons should exist that are not their own antiparticles. Such mesons, possessing what we would now call a net flavor quantum number, could still ‘mix’ through the weak interactions with their respective antiparticles. Therefore, the eigenstates of the resulting particle-antiparticle system would be superpositions of particle and antiparticle \[1\].

The first example of this phenomena was observed in the 1950s for the neutral K meson, $K^0$, and its antiparticle, the $\bar{K}^0$. Figure 1, from an elegant experiment \[2\] done in the 1970s, shows the result of looking at the proportion of $K^0$’s versus that of $\bar{K}^0$’s as a function of time of flight from a production target (where mostly $K^0$’s are produced initially). This is measured by looking at semileptonic decays, for $K^0$ decays result in positive leptons and $\bar{K}^0$ decays in negative leptons (here, positrons, and electrons, respectively).

![Figure 1: The asymmetry in the number of $K^0$ mesons compared to the number of $\bar{K}^0$ mesons in a beam as a function of time \[2\].](image)

\[2\]
At small times, we can see the preponderance of \( K^0 \)s. The eigenstates, which are mixtures of particle and antiparticle, have different masses. They have widths, and inversely lifetimes, that differ by a factor of more than 500, so that we have a dramatic interference pattern as the short-lived \( (\tau_S = 0.89 \times 10^{-10} \text{ s}) \) \( K_S \) dies away, leaving the ‘long-lived’ \( (\tau \approx 5.2 \times 10^{-8} \text{ s}) \) \( K_L \). Defining \( \Delta M_K = M_{K_L} - M_{K_S} \) and similarly for \( \Delta \Gamma_K \), it is found that \( \Delta M_K = 5.3 \text{ ns}^{-1} \approx -\Delta \Gamma_K/2 \) from these and other data \( ^3 \).

If one looks at times much longer than the \( K_S \) lifetime in Figure 1, it can be seen that the surviving \( K_L \) does not have equal particle and antiparticle content: it has slightly more \( K^0 \) than \( \bar{K}^0 \). This is a manifest breaking of CP symmetry in the neutral \( K \) system, usually summarized in terms of the parameter \( \epsilon \). At this workshop, a new measurement of this charge asymmetry based on 300 million semileptonic \( K_L \) decays was reported by the KTeV Collaboration \( ^4 \):

\[
\frac{N(e^+) - N(e^-)}{N(e^+) + N(e^-)} = \frac{2 \text{ Re} \epsilon}{1 + |\epsilon|^2} = 3.320 \pm 0.074 \times 10^{-3},
\]

which is consistent with the previous result \( ^2 \), but more precise and can be used in conjunction with other KTeV results to check conservation of CPT.

CP violation in the \( K^0 \) system was of course first found \( ^5 \) a decade earlier, not by measuring directly the \( K^0 \) versus \( \bar{K}^0 \) content of the \( K_L \), but by looking at its decays into a CP eigenstate, namely \( \pi^+\pi^- \), as shown schematically in

\[ \text{Figure 2: The two quantum mechanical paths for an initial } K^0 \text{ to decay to a final CP eigenstate consisting of a } \pi^+\pi^-. \]
Starting with an initial $K^0$, we see that because of the possibility of mixing there are two quantum mechanical paths to the same final state, whose amplitudes must be added. We take advantage experimentally of the large difference of lifetimes in the neutral $K$ system. Independent of whether we start with a $K^o$ or $\bar{K}^o$, by waiting many $K_S$ lifetimes, nature provides us with the very pure combination of $K^o$ and $\bar{K}^o$ that corresponds to a $K_L$ on the right side of Figure 2. If CP were conserved, the coherent mixture of $K^o$ and $\bar{K}^o$ decay amplitudes would exactly cancel for $K_L \to \pi\pi$. Instead, the observation that the $K_L$ decays into the CP-even eigenstate, $\pi^+\pi^-$, albeit rarely, shows that CP is not conserved and $\epsilon \neq 0$.

2 $B^o - \bar{B}^o$ Mixing

Written in terms of quarks as the fundamental fermionic constituents of matter, we recognize the $K^o$ and $\bar{K}^o$ to be the $d\bar{s}$ and $s\bar{d}$ combinations of down and strange quarks. With the discovery of the charm quark and the bottom quark in the 1970s, nature has given us the richness of three additional systems to investigate, each with strikingly different properties from the neutral $K$ system and from each other. We will return later to the neutral charm mesons, the $D^o = c\bar{u}$ and $\bar{D}^o = u\bar{c}$, and focus our attention on the subjects of this Workshop, mesons containing a $b$ quark.

The combinations of the down and bottom quarks, $B_d = db$ and $\bar{B}_d = b\bar{d}$, form a system where the eigenstates are expected and observed to have nearly the same lifetime: $\Delta\Gamma_d \ll \Gamma$. Previous measurements also indicate that $\Delta M_d \approx 0.8\Gamma_d \approx 0.5$ ps$^{-1}$, very close to 100 times larger than $\Delta M$ for the neutral $K$ system. Precise new measurements of $\Delta M_d$ were presented to this Workshop from $B_d - \bar{B}_d$ oscillations of

$$\Delta M_d = 0.519 \pm 0.020 \pm 0.016 \text{ ps}^{-1}$$

(2)

using hadronic decays in BaBAR [8], and

$$\Delta M_d = 0.463 \pm 0.008 \text{ (stat.)} \pm 0.016 \text{ (syst.) ps}^{-1}$$

$$\Delta M_d = 0.527 \pm 0.032 \text{ (stat.) ps}^{-1}$$

and

$$\Delta M_d = 0.522 \pm 0.026 \text{ (stat.) ps}^{-1}$$

(3)

from dileptons, hadronic decays, and semileptonic decays, respectively, in Belle [7]. Some of these are somewhat above the previous world average
value\(^3\) of 0.472 ± 0.017 ps\(^{-1}\), and it will be interesting to see how the situation develops with further measurements.

![Figure 3: The asymmetry in the number of \(B_d\) mesons compared to the number of \(\bar{B}_d\) mesons as a function of time \(^6\).](image)

The full oscillation of an initial \(B_d\) to a \(\bar{B}_d\) and then back to a \(B_d\), as presented to this Workshop \(^6\), is seen in Figure 3. It is to be contrasted with the oscillation seen in the neutral \(K\) system in Figure 1 and that of the system consisting of the \(B_s = s \bar{b}\) and \(\bar{B}_s = b \bar{s}\), which exhibits features that are different yet again. So far, for the \(B_s\) we have only the lower limit \(^8\): \(\Delta M_s > 15\) ps\(^{-1}\) ≈ 25\(\Gamma_s\) from a combination of the LEP and SLD data. Thus, the \(B_s\) oscillates to a \(\bar{B}_s\) and back again at least four times in an average \(B\) lifetime! In this case we expect \(^9\) a measurable width difference \(\Delta \Gamma_s \approx 0.1\Gamma_s\) and the combined measurements from CDF and LEP are consistent with this \(^9\):

\[
\Delta \Gamma_s / \Gamma_s = 0.16^{+0.08}_{-0.09} .
\]  

(4)

While we don’t have the large lifetime difference of the neutral \(K\) system that allowed us to study the particle \textit{versus} antiparticle content of the \(K_L\),
we can gain information on the same quantity in the neutral B system by measuring the asymmetry between the rates of production of two positive leptons compared to two negative leptons when a $B^0\bar{B}^0$ pair is produced in electron-positron annihilation and both decay semileptonically (after either the $B$ or $\bar{B}^0$ mixes). As in the $K^0$ system, this CP-violating asymmetry is expected to be small. Indeed, at this workshop a new value with considerably increased precision, but still consistent with zero, was reported for the $B_d$ system by the CLEO Collaboration \cite{10}. When combined with a previous analysis that uses both hadronic and semileptonic decays, they find that for $\epsilon_B$ defined analogously to $\epsilon$ in the neutral K system,

$$\frac{\text{Re} \epsilon_B}{1 + |\epsilon_B|^2} = 0.0035 \pm 0.0103 \pm 0.0015 \ .$$

(5)

3 Neutral Meson Mixing

At this point, we take a theoretical interlude from the procession of beautiful experimental results to recap the formalism of mixing in particle-antiparticle systems. If we label the meson by the index 1 and the anti-meson by the index 2, then the time dependence of this two state system is determined by a $2 \times 2$ matrix

$$\begin{pmatrix} M_{11} - \frac{i}{2} \Gamma_{11} & M_{12} - \frac{i}{2} \Gamma_{12} \\ M_{21} - \frac{i}{2} \Gamma_{21} & M_{22} - \frac{i}{2} \Gamma_{22} \end{pmatrix} \ .$$

(6)

We have split this $2 \times 2$ matrix into hermitian, $M$, and antihermitian, $i\Gamma$, parts, so that:

$$M_{12} = M_{21}^{*} \ ,$$

$$\Gamma_{12} = \Gamma_{21}^{*} ,$$

(7)

and $M_{11}$, $M_{22}$, $\Gamma_{11}$, and $\Gamma_{22}$ are real. If we further assume that CPT invariance holds, then

$$M_{11} = M_{22} = M \ ,$$

$$\Gamma_{11} = \Gamma_{22} = \Gamma \ ,$$

(8)

and the matrix now reads

$$\begin{pmatrix} M - \frac{i}{2} \Gamma & M_{12} - \frac{i}{2} \Gamma_{12} \\ M_{12}^{*} - \frac{i}{2} \Gamma_{12}^{*} & M - \frac{i}{2} \Gamma \end{pmatrix} \ .$$

(9)
The diagonalized matrix gives the mass and width of the eigenstates. Furthermore, CP is conserved if and only if \( \text{Im}(M_{12}\Gamma_{12}^*) = 0 \). This could happen if \( M_{12} \) and \( \Gamma_{12} \) have the same phase (nearly true for the neutral K system), or if one of them vanishes (nearly true for \( \Gamma_{12} \) in the neutral B systems).

The large diagonal elements of the matrix get dominant contributions from the quark masses and the strong interactions. The flavor-changing off-diagonal elements get contributions only from the weak interactions. The absorptive off-diagonal element, \( \Gamma_{12} \), can be related to a sum over on-shell intermediate states that couple to both the meson and the anti-meson. For the dispersive \( M_{12} \), an infinite sum of virtual intermediate states of arbitrarily increasing mass are relevant. \( M_{12} \) can be computed in the Standard Model from weak interaction box diagrams involving W’s and quarks. QCD corrections to these weak interaction processes are important, but are under good control, have been done in leading order and next-to-leading order. At the vertices of these box diagrams are the elements of the Cabibbo-Kobayashi-Maskawa matrix, to which we now turn our attention.

### 4 The Cabibbo-Kobayashi-Maskawa Matrix

In the Standard Model with \( SU(2) \times U(1) \) as the gauge group of electroweak interactions, both the quarks and leptons are assigned to be left-handed doublets and right-handed singlets. The quark mass eigenstates differ from the weak eigenstates, and the matrix relating these bases was defined for six quarks and given an explicit parametrization by Kobayashi and Maskawa \[11\] in 1973. It generalizes the four-quark case, where the matrix is parametrized by a single angle, the Cabibbo angle \[12\].

By convention, the mixing is often expressed in terms of a \( 3 \times 3 \) CKM matrix \( V \) operating on the charge \( -e/3 \) quark mass eigenstates \( (d, s, \text{ and } b) \):

\[
\begin{pmatrix}
  d' \\
  s' \\
  b'
\end{pmatrix} = \begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{ts} & V_{tb}
\end{pmatrix} \begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix}. \tag{10}
\]

As this matrix \( V \) is unitary, it can physically be fully specified by four real parameters. These can be taken to be three “rotation” angles and one phase. CP violation has a natural place and occurs if the phase is not \( 0^\circ \) or
180° and the other angles are not 0° or 90°, i.e., if there is non-trivial mixing between each pair of generations of quarks and there is a non-trivial phase.

Decades of experimental effort have produced a great deal of information about the magnitude of the CKM matrix elements from semileptonic decays, neutrino reactions, and most recently, hadronic $W$ decays [13]. We know experimentally that all three angles that characterize the CKM matrix are small but non-zero. In the absence of a well-motivated argument to the contrary, there is an expectation that the single non-trivial phase should be non-zero as well. If CP violation does arise from the CKM matrix, it gives rise to both a natural scale and a special pattern for CP-violating effects (and for flavor-changing-neutral-current effects generally).

5 The Unitarity Triangle

Direct and indirect information on the less precisely known elements of the CKM matrix is neatly summarized in terms of the “unitarity triangle,” one of six such triangles that correspond to the unitarity condition applied to two different rows or columns of the CKM matrix. Unitarity applied to the first and third columns yields

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

The unitarity triangle is just a geometrical presentation of this equation in the complex plane. We can always choose to orient the triangle so that $V_{cd} V_{cb}^*$ lies along the horizontal or real axis, as it is in a number of standard parametrizations. Setting diagonal elements of the CKM matrix to unity (which is good to a few percent or better) and recognizing that $V_{cd} = s_{12}$, the sine of the Cabibbo angle, Eq. (11) becomes

$$V_{ub}^* + V_{td} = s_{12} V_{cb}^* .$$

Rescaling the triangle by a factor $[1/|s_{12} V_{cb}|]$ so that the base is of unit length, the coordinates of the vertices become

$$A(\text{Re}(V_{ub})/|s_{12} V_{cb}|, -\text{Im}(V_{ub})/|s_{12} V_{cb}|), B(1, 0), C(0, 0) .$$

In the Wolfenstein parametrization [14], the coordinates of the vertex $A$ of the rescaled unitarity triangle are simply $(\rho, \eta)$. 7
A non-trivial unitarity triangle, given the other information that we have on the magnitudes of the CKM matrix elements, implies that there is CP violation in the Standard Model and vice versa. Since we know the length of the base, \( |V_{cb}s_{12}| \), quite well and that of another side, \( |V_{ub}| \), moderately well, the complete triangle could be determined by either a measurement of the length of the third side \( |V_{td}| \), one of the angles, or by some condition that involves a combination of these.

Ultimately we want to obtain multiple determinations of the triangle to test the Standard Model as a description of weak interactions and of CP violation. A failure of the multiple determinations to agree would lead us to our even more important goal of getting clues to the physics that lies beyond the Standard Model.

The traditional inputs to determination of the unitarity triangle are \( |V_{cb}| \) and \( |V_{ub}| \) from semileptonic B decays, plus, under the assumption that they originate in the Standard Model, \( \epsilon \) from the neutral K system, \( \Delta M_d \) from \( B_d \) mixing, and (limits on) \( \Delta M_s \) from \( B_s \) mixing. Reviews of earlier measurements [15] of \( |V_{cb}| \) and \( |V_{ub}| \), as well as new measurements [10], [16], [17] were presented to this Workshop. In particular, a different type of analysis [17] from CLEO that uses moments in inclusive B semileptonic and \( b \to s\gamma \) decays to fix the heavy-quark-effective-theory parameters gives another way of determining \( |V_{cb}| \) with error bars that are at least comparable to other methods and should lead to a more precise value of \( |V_{ub}| \) in the near future.

The enterprise of trying to pin down the unitarity triangle has been underway for more than a decade, and great progress has been made. It is instructive to go back a dozen years to when the B-factories were just being put forward to measure the angles of the unitarity triangle. Not only were the uncertainties at that time considerably larger on the magnitudes of the CKM relevant matrix elements, but because the top mass was not known, the constraints from \( \epsilon \) and B-mixing had to be applied with the added uncertainty of a big potential range for \( m_t \). This is illustrated [18] in Figure 4, where the case of \( m_t = 160 \) GeV has been picked out from many other figures in 1989 that covered a then-perceived range of 80 to 200 GeV for \( m_t \).
Figure 4: The restrictions [18] on the position of the vertex A of the unitarity triangle in the $\rho - \eta$ plane in 1989 for a top quark mass, $m_t = 160$ GeV.

Compare this with the more recent status [13] of the unitarity triangle shown in Figure 5. By not dividing by the length of the base, we emphasize the accuracy ($\sim 10^{-3}$ of the magnitude of the diagonal elements of the matrix) that is now needed to make further progress. We are indeed entering an era of precision CKM measurements.

The biggest uncertainties remaining are theoretical in character. They lie particularly in the hadronic matrix elements of operators containing quark
Figure 5: Constraints on the position of the vertex, A, of the unitarity triangle following from $|V_{ub}|$, $B$ mixing, and $\epsilon$ are indicated. A possible unitarity triangle is shown with A in the preferred region [13].

fields. There are intensive discussions underway, both of the size of these theoretical errors and of how to treat them. This includes a number of recent papers and contributions to this Workshop [13], [20], [21], [22]. It was the subject of a panel at the B2000 meeting as well [23]. While this may appear to be a controversy merely evoking strongly stated positions among a small segment of the community, it has important physics consequences [24]. Taking smaller uncertainties in $|V_{ub}|$ and the hadronic parameters involved in $B_d$ mixing (to extract $|V_{td}|$), leads some to claim [23], [24] that there is a strong likelihood that we must have a non-trivial triangle, i.e., that there is CP violation arising from the CKM matrix, without imposing any constraint from $\epsilon$ in the neutral K system (whose use would already be assuming that CP violation originates in the CKM matrix). Others [21], [23], including me, are not ready to draw such a strong conclusion yet. Continued progress is being made [9], [23], [26] in lattice QCD calculations to determine the hadronic parameters. Ultimately, they should produce results with an accuracy that is comparable to those from the experimental measurements themselves.

Where will the next major advance come in this area? I believe that it will come with the measurement of $B_s$ mixing at the Tevatron collider. The
prospects [27] for such a measurement were described at this Workshop. It appears that if the mixing originates through Standard Model physics, $B_s$ mixing will be measured rather accurately, and that will allow the comparison with $B_d$ mixing to give $|V_{ts}/V_{td}|$ with small theoretical uncertainties. Since $|V_{ts}|$ must be very close to $|V_{cb}|$ with three generations, this in turn will fix $|V_{td}|$ in the Standard Model with small errors and determine the unitarity triangle from measurements of the three sides. Then we will see if this is consistent with the other information we will have on the angles or the area of the triangle.

6 CP Violation Involving $B^o$ Mixing

The decay of an initial $B^o$ to a final state, $f$, can occur through an amplitude corresponding to $B^o \rightarrow f$, or by the $B^o$ mixing to a $\bar{B}^o$, followed by the $\bar{B}^o$ decaying to the same final state through an amplitude corresponding to $\bar{B}^o \rightarrow f$. This gives rise to the situation [28] shown in Figure 6.

Figure 6: Two quantum mechanical paths for $B^o$ decay through mixing and decay to a final state $f$.

On the one hand, note the close theoretical similarity to the situation involving mixing and decay in the neutral $K$ system that we discussed earlier. On the other hand, because of the lifetime of the $B$, instead of the hundreds of meters from production to decay that contemporary $K_L$ decay experiments involve, at an $e^+e^-$ B-factory experiments must be able to measure
the distance from the production of a $B$ to its decay of hundreds of microns – roughly a million times smaller!

If $f$ is a CP eigenstate, $f_{CP}$, and we take the neutral $B$ eigenstates to have the same lifetime, then the time-dependent rate for an initial $B^0/\bar{B}^0$ to decay into $f_{CP}$ is

$$\frac{d\Gamma[B^0(t)/\bar{B}^0(t) \rightarrow f_{CP}]}{dt} = e^{-\Gamma t} \left[ 1 \pm \eta_{CP} \sin 2\phi \sin(\Delta M t) \right],$$  \hspace{1cm} (14)

where $\eta_{CP}$ is the CP-eigenvalue of the final state and the phase $\phi$ arises from CKM matrix elements relevant to the particular decay. In simple cases where one weak amplitude dominates, $\phi$ turns out to be just an angle of the unitarity triangle. These angles are taken to be $\alpha = \phi_2$, $\beta = \phi_1$, and $\gamma = \phi_3$ at the vertices A, B, and C, respectively, of the unitarity triangle.

7 CP Violation in B Decay Amplitudes

One can also have CP-violating observables that do not involve mixing. They occur through the interference of two decay amplitudes that contribute to a given process and its CP-conjugate process. Under charge conjugation, the weak phases change sign, while the strong phases do not, as both C and P separately are conserved by the strong interactions. To get a non-zero rate difference, one must have at least two amplitudes with different weak and strong phases. In the $B_d$ and $B_s$ systems, there are simple relations between CP-violating rate differences for processes obtained by interchanging $d$ and $s$ quarks [29].

An example is provided by the neutral $K$ system, where interference of tree and penguin amplitudes, which have different weak phases, for the decay $K \rightarrow \pi\pi$ give a non-zero rate difference characterized by the parameter $\epsilon'$, with \cite{3} $\epsilon'/\epsilon \sim 2 \times 10^{-3}$. Many possibilities for such CP-violating asymmetries can be found in $B$ decays, but their observation remains for the future.

8 The B-factories

Before looking at the new experimental results on CP violation in the neutral $B$ system, one must salute the members of the accelerator physics community that designed and built the asymmetric electron-positron colliding beam machines, the B-factories, that allow these experiments to be done at all. The
performance of PEPII at SLAC [30] and of KEKB at KEK [31] have been absolutely remarkable. The peak luminosity of PEPII has exceeded the design goal of $3 \times 10^{33}$ cm$^{-2}$s$^{-1}$ and KEKB was operating above $2.4 \times 10^{33}$ cm$^{-2}$s$^{-1}$ during the Workshop. A dozen years ago, there were plenty of skeptics that one could have amperes of positrons and electrons of different energies colliding to produce physics results. But today we sit solidly in the range of integrated luminosities that were foreseen [8] at that time as needed to produce a statistically significant measurement of a CP-violating asymmetry.

This success has given us planning toward realizing what would once have seemed truly amazing possibilities. PEPII is on an upgrade path [30] that gets to luminosities of $5 \times 10^{33}$ this year and to $10^{34}$ in 2003. Feasibility studies are being conducted of several avenues to $3 \times 10^{34}$ cm$^{-2}$s$^{-1}$. KEKB [31] plans call for reaching $7 \times 10^{33}$ cm$^{-2}$s$^{-1}$ in 2002-2003 and more than $10^{34}$ in 2005-2006. These luminosities inspired an exciting session [32] of this Workshop, “$10^{34}$ and Beyond,” to examine the experimental possibilities that are opened up by such luminosities.

9 CP Violation in the B System: Measurement of $\sin 2\beta = \sin 2\phi_1$

The BaBar and Belle Collaborations have both presented new data to this Workshop on tagged $B_d^o$ and $\bar{B}_d^o$ decays to final CP eigenstates, $f_{CP}$, to observe a time-dependent CP asymmetry [33], [34]. Both employ the “golden” final state $J/\psi K_S$, plus $\psi(2S)K_S$ and $J/\psi K_L$. Belle uses a few other modes as well. Through the time-dependent asymmetry, these decays all provide a measure of $\sin 2\beta = \sin 2\phi_1$ from the unitarity triangle in a theoretically clean way. Furthermore, the high-performance subsystems of both detectors all work so as to make this prime measurement for which they were designed.

The results are

$$\sin 2\beta = 0.34 \pm 0.20 \pm 0.05 \text{ (BaBar [33])}$$

$$\sin 2\phi_1 = 0.58 \pm 0.32 \pm 0.09 \text{ (Belle [34])}$$

These results are consistent with each other and with previous measurements. The present world average is

$$\sin 2\beta = 0.48 \pm 0.16$$
Thus, combining all the data, it is already unlikely that CP is conserved in the combination of neutral $B$ mixing and decay. These results are also consistent with the Standard Model and a single phase from the CKM matrix as the origin of CP violation. For example, from Figure 5, $\sin 2\beta$ should lie in the range from 0.5 to 0.9.

We can now see getting to the goal of errors of 0.1 or less for the “golden” mode, $J/\psi K_S$, and having confirmatory measurements in several other modes. However, at the present, the asymmetry data for just the final state $J/\psi K_S$ with the $K_S$ decaying to $\pi^+\pi^-$ are (with statistical errors only) $0.25 \pm 0.26$ and $1.21^{+0.40}_{-0.47}$ from BaBar and Belle, respectively. We need a little more patience to get to the decisive test for which we have been waiting many years.
10 Measurement of the Other Angles of the Unitarity Triangle

Early on, it seemed that $\sin 2\beta$ would be the first of the CP-violating asymmetries to be measured. This has indeed turned out to be true, as we have just seen. The other angles of the unitarity triangle have not only proven to be harder than expected to get at experimentally, but they have also turned out to be theoretically more complicated as well.

For $\sin 2\alpha = \sin 2\phi_2$, the mode that attention was originally focused on was $B^o/\bar{B}^o \to \pi^+\pi^-$. Not only has the branching ratio for this mode turned out to be considerably smaller than had been hoped (see the next section), but it was that in addition to a tree amplitude, penguin diagrams with different weak phases likely enter in a significant way. Much theoretical work that depends on measurements of other two body modes plus $SU(2)$ and/or $SU(3)$ symmetry has gone into finding ways to salvage the situation. The measurement of other decay modes such as $\sin 2\alpha$ could prove important as well. Removing this “penguin pollution” to re-establish a clean measurement of $\sin 2\alpha$ has been reviewed both at this Workshop [29] and elsewhere [35].

For $\sin 2\gamma = \sin 2\phi_3$, many methods have been proposed [29], [35]. Two recent ideas requiring very high luminosities were the subject of talks [36], [37] at this Workshop. During the course of the Workshop I inquired of a number of my theoretical colleagues as to where the first rough measurement of $\gamma$ will come from. The consensus was that most likely a comparison [38] of accurately measured branching ratios in $B \to K\pi$ decays (where there is an interference of tree and penguin amplitudes that involves the weak phase $\gamma$) would yield the first information directly restricting the range of gamma. Eventually, a precise value was seen to come from $B_u \to D^oK$ rates at a high luminosity electron-positron collider [32], [35] or from time-dependent $B_s(t) \to D_sK$ measurements at hadron colliders. While the latter measurements might begin during Run II of the Tevatron [27], they are primarily the domain of the physics program of the next generation of hadron collider experiments, BTEV [39] and LHCb [40].

11 Rare B Decays

The measurement of many branching ratios for B decays at the $10^{-5}$ level and below is proceeding apace at BaBar, Belle, and CLEO. This Workshop
had more than half a dozen talks on measurements of rare B decays \cite{11}, \cite{12}, \cite{13}, \cite{14}, \cite{15}, \cite{16} plus papers in the poster sessions, and more than that number of theoretical talks examining how to understand the mechanism by which such decays proceed \cite{29}, \cite{48}, \cite{49}, \cite{50}, \cite{51}, \cite{52}, \cite{53}, \cite{54} and how new physics might show up \cite{55}, \cite{56}, \cite{57}, plus more papers in the poster sessions. I only have space to call attention to a few of the many interesting developments reported here.

- The measurements of the branching ratios for $B$ decays to two pseudoscalar mesons have settled down and now we have substantial agreement between BaBar \cite{42}, Belle \cite{43}, and CLEO \cite{44}. In particular, for the branching ratio for $B^0 \rightarrow \pi^+ \pi^-$ they report $4.1 \pm 1.0 \pm 0.7 \times 10^{-6}$, $5.9^{+0.24}_{-0.21} \pm 0.5 \times 10^{-6}$, and $4.3^{+1.6}_{-1.4} \pm 0.5 \times 10^{-6}$, respectively. As noted above, even aside from theoretical difficulties, this low branching ratio makes deriving information on $\sin 2\alpha$ that much more difficult.

- Systematic studies of all the “Cabibbo-suppressed” $B \rightarrow DK^-$ and $B \rightarrow D^*K^-$ decays shows that their branching ratios are at the expected level of $\sim 0.07$ times their pionic counterparts \cite{43}.

- Inclusive and exclusive measurements of B decays that correspond to $b \rightarrow s\gamma$ are becoming standard measurements \cite{17}, \cite{45}, and we can look forward soon to measurements of $b \rightarrow s\mu^+\mu^-$. The corresponding theoretical situation is in rather good shape \cite{48}.

- Important theoretical progress is being made as well, centering on understanding QCD as it applies to B non-leptonic decays \cite{19}, \cite{50}, \cite{51}, \cite{53}, \cite{54}. Specific questions are where and how factorization applies and what is the importance of penguin diagrams in the overall picture. These issues were the focus of the presentation \cite{51} on factorization and penguin amplitudes in $B \rightarrow K\pi$ decays, where precise data should be forthcoming that will clarify whether we now have a good theoretical understanding of these and similar decays.

12 D, K, and Lepton Physics

Our review of what is happening and will happen in B physics is not complete without taking into account the complementary experimental and theoretical
work for other quark and lepton flavors which relate to the same theoretical parameters and questions. As pointed out in an excellent review at this Workshop [58], charm physics, aside from its own merits, acts as a staging area both experimentally and theoretically for the assault on B physics. In addition, it may give us some surprises of its own regarding new physics. The particular places to watch are the measurements of $x = \Delta M/\Gamma$ and $y = \Delta \Gamma/\Gamma$ in the neutral D system and on CP violating asymmetries, as we push to the few percent level described at this Workshop [59], [60] and smaller in the years to come.

Experiments involving K mesons continue to provide alternate measurements of rare and CP-violating processes that allow theoretically clean determinations the CKM parameters. The future programs of KTEV [61] and NA48 [62] were described at this Workshop, and are part of a bigger worldwide effort that aims at measuring branching ratios, such as that for the “golden mode,” $K_L \rightarrow \pi^0 \nu \bar{\nu}$, down to the $10^{-11}$ level [63].

Finally, there are the measurements of the magnetic dipole moment of the muon and the search for (T-violating) electric dipole moments. We heard about an improved limit on the electric dipole moment of the tau [64] at this Workshop and through another talk [65] shared in the excitement generated by the recent measurement of the magnetic moment of the muon, which is in tantalizing disagreement with Standard Model predictions.

13 Conclusion

We have reached the time where the colliders, detectors, and experimental collaborations are in place to carry out the long-planned exploration of CP violation in the B system. Theory has made considerable progress as well in understanding how to relate the measurements that will be made in the next few years to the fundamental parameters of the theory, multiple routes of varying experimental difficulty and theoretical cleanliness to those parameters, and in understanding the effects that various types of physics beyond the Standard Model could have on CP-violating effects in the B system.

At this Workshop, exciting new results from BaBar and Belle on the CP-violating asymmetry that corresponds to $\sin 2\beta = \sin 2\phi_1$ have been presented. We can now see that rather precise measurements of the $\beta = \phi_1$ will be made in the next couple of years. Those, together with rough information on the other angles of the unitarity triangle and precise magnitudes for the
CKM matrix elements that will come in the same time frame will make for a
decisive test of whether the Standard Model picture for the weak interactions
between quarks and CP violation is correct.

The B-Factory and hadron collider experiments are also exploring a host
of related issues, from precise measurements of mixing in the neutral B sys-
tems to rare, flavor-changing-neutral-current decays and CP violation with-
out mixing in B decays. So prepare for enormous amounts of data and great
physics!

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