This overview of what we can hope to learn from high-statistics experiments in $B$ physics in the next few years includes: (a) a review of parameters of the Cabibbo-Kobayashi-Maskawa (CKM) Matrix; (b) direct determination of magnitudes of CKM elements; (c) forthcoming information from studies of kaons; (d) CP violation in $B$ decays; (e) aspects of rate measurements; (f) the role of charm-anticharm annihilation; (g) remarks on tagging; and (h) effects beyond the standard model.

I. INTRODUCTION

The violation of CP symmetry in the decays of neutral kaons remains a mystery more than thirty years after its discovery. A candidate theory for this violation, involving phases in the Cabibbo-Kobayashi-Maskawa (CKM) matrix, predicts large CP-violating effects in the decays of $B$ mesons. As a result, a massive experimental assault is under way to study those decays. In the present review we discuss some types of studies that will be possible in high-statistics experiments, whether by advances in background reduction in hadronic experiments or by increased luminosity in electron-positron collisions. This report is in part a summary of other theoretical contributions at the Beauty '97 Workshop, which should be consulted for details.

We begin in Section II with a brief overview of the CKM parameters and why we care about their precise values. Section III is devoted to direct measurements of magnitudes of CKM elements. Experiments with kaons, some of which are very close to presenting new results, will provide partial information (Sec. IV). Various ways of detecting CP violation in $B$ decays exist (Sec. V); we concentrate on measurements of rates for rare processes (Sec. VI) which do not require time-dependent studies. Some brief remarks are made in Section VII about the role of charm-anticharm annihilation in $B$ decays, and in Section VIII about progress in identifying the flavor of a neutral $B$ meson at time of production. Some tests of physics beyond the standard model are mentioned in Section IX, while Section X concludes.

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Figure 1: Unitarity triangle for CKM elements. We show in the complex plane the relation (3) divided by the normalizing factor $A\lambda^3$.

**II. WHY WE CARE ABOUT CKM PARAMETERS**

We give an abbreviated version of a description which may be found in more detail elsewhere [4]. The CKM matrix element $V_{ij}$ describes the charge-changing transition of a left-handed down-type quark $j$ to a left-handed up-type quark $i$. A parametrization sufficiently accurate for present purposes is that of Wolfenstein [5]:

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

The quantity $\lambda = 0.2205 \pm 0.0018 = \sin \theta_C$ [8, 9] expresses the suppression of $s \rightarrow u$ decays with respect to $d \rightarrow u$ decays [2, 8]. This parameter describes the $u, d, s$, and $c$ couplings via the upper left $2 \times 2$ submatrix of $V$ [9].

When a third family of quarks is added, three more parameters are needed. One may express them in terms of (1) the strength characterizing $b \rightarrow c$ decays, $A\lambda^2 = 0.0393 \pm 0.0028$ [10, 11] so that $A = 0.81 \pm 0.06$ (see [12], [13] for slightly different values); (2) the magnitude of the $b \rightarrow u$ transition element measured in charmless $b$ decays, $V_{ub}/V_{cb} = 0.08 \pm 0.02$ [11] so that

$$(\rho^2 + \eta^2)^{1/2} = 0.36 \pm 0.09 \quad ; \quad (2)$$

(3) the phase of $V_{ub} = A\lambda^3(\rho - i\eta)$. Unitarity of the CKM matrix implies that the scalar product of the complex conjugate of a row with any other row should vanish, e.g.,

$$V_{ud}^* V_{td} + V_{us}^* V_{ts} + V_{ub}^* V_{tb} = 0 \quad . \quad (3)$$

Since $V_{ud}^* \approx 1$, $V_{us}^* \approx \lambda$, $V_{ts} \approx -A\lambda^2$, and $V_{tb} \approx 1$ we have $V_{td} + V_{ub}^* = A\lambda^3$. Dividing (3) by $A\lambda^3$, since $V_{ub}^*/A\lambda^3 = \rho + i\eta$, $V_{td}/A\lambda^3 = 1 - \rho - i\eta$, one obtains the triangle shown in Fig. 1. Here the angles $\alpha, \beta, \text{and } \gamma$ are defined as in [14]. The value of $V_{ub}^*/A\lambda^3$ may then be depicted as a point in the $(\rho, \eta)$ plane. To resolve the major remaining ambiguity in the determination of the CKM matrix elements, i.e., the phase of $V_{ub}$, the shape of the unitarity triangle, or the value of $V_{td}$, one must resort to indirect means, which involve loop diagrams.
Box diagrams involving $u$, $c$, and $t$ in loops contribute to the virtual $b\bar{d} \leftrightarrow d\bar{b}$ transitions which mix $B^0$ and $\bar{B}^0$. The leading contribution at high internal momentum in these diagrams cancels as a consequence of (3). The remaining contribution is dominated by the top quark since all products of CKM elements $V_{qb}V_{qd}^*$ are of order $\lambda^3$ while $m_t \gg m_c, m_u$.

In the calculation of the effect of the box diagram [15] one needs several parameters, the most recent values of which are $m_t = 175.5 \pm 5.5$ GeV/$c^2$ [16], $M_W = 80.40 \pm 0.08$ GeV/$c^2$ [16], $m_B = 5.279$ GeV/$c^2$ (see [7]), and $f_B \sqrt{B_B} = 200 \pm 40$ MeV [11, 12]. Here $f_B$ is the $B$ meson decay constant, defined so that the matrix element of the weak axial-vector current $A_\mu \equiv \bar{b} \gamma_\mu \gamma_5 d$ between a $B^0$ meson and the vacuum is $(0|A_\mu|B^0(p)) = i p_\mu f_B$. The factor $B_B$ expresses the degree to which the box diagrams provide the contribution to $B - \bar{B}$ mixing. The result involves a QCD correction $\eta_B = 0.55$ [17]. The mixing amplitude [18] is $\Delta m_d = 0.472 \pm 0.018$ ps$^{-1}$, where the subscript refers to the mixing between $B^0 \equiv \bar{b}d$ and $\bar{B}^0 \equiv bd$. The corresponding estimate of $|V_{td}|$ (see Ref. [9] for more details) leads, once we factor out a term $A \lambda^3$, to the constraint [13]

$$|1 - \rho - i\eta| = 1.01 \pm 0.22$$

(4)

A key constraint comes from CP-violating $K^0-\bar{K}^0$ mixing. One can parametrize the mass eigenstates as $K_S \simeq K_1 + \epsilon K_2$, $K_L \simeq K_2 + i\epsilon K_1$, where $|\epsilon| \simeq 2 \times 10^{-3}$ and the phase of $\epsilon$ turns out to be about $\pi/4$. The parameter $\epsilon$ encodes all current knowledge about CP violation in the neutral kaon system. Its origin is still the subject of hypothesis. One possibility, proposed [20] immediately after the discovery and still not excluded, is a “superweak” CP-violating interaction which directly mixes $K^0 = d\bar{s}$ and $\bar{K}^0 = s\bar{d}$. The presence of three quark families [3] poses another opportunity for explaining CP violation through box diagrams involving $u$, $c$, and $t$ quarks. With three quark families, phases in complex coupling coefficients cannot be removed by redefinition of quark phases. Within some approximations [21], the parameter $\epsilon$ is directly proportional to the imaginary part of the mixing amplitude. Its magnitude was given for arbitrary $m_t$ in Ref. [15] and implies the constraint [3]

$$\eta(1 - \rho + 0.44) = 0.51 \pm 0.18$$

(5)

where the term $1 - \rho$ corresponds to the loop diagram with two top quarks, and the term 0.44 corresponds to the additional contribution of charmed quarks. The major source of error on the right-hand side is the uncertainty in the parameter $A \equiv V_{tb}/\lambda^2$. Eq. (5) can be plotted in the $(\rho, \eta)$ plane as a band bounded by hyperbolae with foci at $(1.44,0)$.

The most recent constraint is to a lower bound on the mixing parameter $\Delta m_s$ for $B^0_s-\bar{B}^0_s$ mixing: $\Delta m_s > 10.2$ ps$^{-1}$ [18]. The loop diagrams for $\Delta m_s$ are dominated by the CKM element $V_{ts}$, in contrast to those for $\Delta m_d$ which are dominated by $V_{td}$. Thus a measurement of $\Delta m_s/\Delta m_d$ implies a limit on $|V_{ts}/V_{td}|$. The result [18] is $|V_{ts}/V_{td}| > 3.8$, implying $|1 - \rho - i\eta| < 1.19$. This excludes a small portion of the region allowed by the $B^0-\bar{B}^0$ mixing constraint [11].

The $(\rho, \eta)$ region allowed by all the above constraints is plotted in Fig. 2. The boundaries are dominated by theoretical uncertainties.

A region centered about $\rho \simeq 0.05, \eta \simeq 0.35$ is permitted. Nonetheless, the CP violation seen in kaons could be due to an entirely different source, such as a superweak
mixing of $K^0$ and $\bar{K}^0$ [20]. In that case one could still accommodate $\eta = 0$, and hence a real CKM matrix, by going slightly outside the bounds based on $|V_{ub}/V_{cb}|$ or $B-\bar{B}$ mixing. This circumstance is illustrated by a considerably more permissive $(\rho, \eta)$ plot presented in Ref. [22], for which the $B-\bar{B}$ mixing constraint entails only $0.65 < |1 - \rho - i\eta| < 1.63$. Even with this relaxed constraint, the range of values of $\sin(2\beta)$ is quite restricted, lying roughly between 0.4 and 0.9 (assuming that $\sin(2\beta) > 0$ as implied by the value of $\epsilon$!).

Thus, there is much potential for uncovering new physics simply by observing a value of $\sin(2\beta)$ outside the range 0.4–0.9. Such new physics is most likely to be manifested most prominently (though not exclusively) through additional contributions to mixing, which can affect the determination of $\sin(2\beta)$ via a CP asymmetry in the $B^0 \to J/\psi K_S$ mode.

The $(\rho, \eta)$ plot can be useful in several ways. (1) It permits anticipation of standard model expectations for $K \to \pi\nu\bar{\nu}$, $B$ decays, and other experiments. (2) It permits one to exclude a superweak model in which the CP-violating asymmetries in $B \to J/\psi K_S$ and $B \to \pi^+\pi^-$ are equal and opposite [23]. (3) It allows one to constrain schemes in which CKM matrix elements are related to quark masses, typically by means of a series of discrete assumptions. (4) It allows one to expose inconsistencies in the standard CKM through overconstrained measurements of the sides and angles of the unitarity triangle. New-physics effects are seen typically (though not exclusively) in mixing and penguin amplitudes (e.g., those dominating the $b \to s\gamma$ and $b \to s\ell^+\ell^-$ subprocesses) before showing up in direct decays, because loop effects are more sensitive to these effects.
III. MAGNITUDES AND RATIOS OF CKM MATRIX ELEMENTS

A. $|V_{cb}|$. Improvement of accuracy in $|V_{cb}|$ is particularly important since the dominant contribution to $\epsilon$ in CP-violating $K$–$\bar{K}$ mixing behaves as $|V_{cb}|^4$. In inclusive decays $B \to X_s \ell \nu \ell \nu$ [24] it will be useful to measure $M(X_s)$ and moments $\langle E_t^\ell \rangle$ of the lepton energy $E_t$. The fact that $m_b - m_c$ is constrained to lie in a narrow range between 3.34 and 3.4 GeV/$c^2$ helps to reduce uncertainty due to the the overall scale of $m_b$ and $m_c$ [25]. One hopes for an eventual determination of $|V_{cb}|$ to an error of 5%.

Among exclusive decays the process $B \to D^* \ell \nu \ell \nu$ holds the best hope of yielding an accurate value of $|V_{cb}|$. One uncertainty in the corresponding form factors [26] is associated with the contribution of virtual pions: e.g., $B \to B^* \pi \to D \pi \ell \nu \ell \nu \to D^* \ell \nu \ell \nu$. The $D^*D\pi$ coupling constant $g$ enters in this calculation and could in principle be measured: $\Gamma(D^{*+} \to D^0\pi^+) = (0.2$ MeV$/g^2)$. One expects $g \simeq 1/2$, posing a real challenge to experimentalists. One might be able to “calibrate” the $D^*$ widths if it were possible to calculate the rate for $D^{*0} \to D^0\gamma$ accurately.

B. $|V_{ub}/V_{cb}|$. Information on $|V_{ub}/V_{cb}|$ constrains $(\rho^2 + \eta^2)^{1/2}$ and bears improvement, as shown in Fig. 2. Inclusive decays [24] $B \to X\ell \nu \ell \nu$ with $M_X < m_D$ would allow one to study a larger part of the spectrum in charmless semileptonic decays than is possible with the current method, which looks at the “tail of the elephant” by measuring the lepton energy spectrum beyond the charm endpoint.

Exclusive decays can improve information on $|V_{ub}/V_{cb}|$ [24] by studying $B \to \rho \ell \nu \ell \nu$ and relating its form factors to those in the process $D \to \rho \ell \nu \ell \nu$, which in turn can be related by flavor SU(3) to $D \to K^* \ell \nu \ell \nu$. It may also be possible to gain adequate understanding of the form factor in $B \to \pi \ell \nu \ell \nu$ [25], for which a measurement at the 25% level now exists [23]. One foresees an eventual determination of $|V_{ub}/V_{cb}|$ to 10%.

C. $|V_{ts}/V_{td}|$. As mentioned, the $(\rho, \eta)$ limits based on $x_s \equiv (\Delta m/\Gamma)_{B_s}$ are beginning to encroach upon the otherwise-allowed region. The limit $\Delta m_s/\Delta m_d > 21.2$ (95% c.l.) [18] corresponds to $\Delta m_s > 10.2$ ps$^{-1}$ and $x_s > 16$. The ratio

$$\sqrt{\frac{\Delta m_s}{\Delta m_d}} \sim \frac{f_{B_s}}{f_B} \frac{|V_{ts}|}{|V_{td}|},$$

combined with the quark-model upper limit $f_{B_s}/f_B < 1.25$ [30] (consistent with lattice gauge estimates), implies $|V_{ts}/V_{td}| > 3.8$ and $|1 - \rho - i\eta| < 1.19$ as shown in Fig. 2. The allowed region permits $|1 - \rho - i\eta| > 0.6$, or $x_s < (1.19/0.6)^2 \simeq 64$.

D. $|V_{ub}/V_{td}|$. A direct measurement of the combination $f_B|V_{ub}|$ is possible through the leptonic decay of the $B^+$:

$$\Gamma(B^+ \to \{\mu^+\nu_\mu\} \bar{\tau}^+\nu_\tau) = \left\{ \begin{array}{cc} 1.1 \times 10^{-7} & \text{if } f_B \langle f_\pi \rangle^2 |V_{ub}|^2 \frac{0.003}{10^{-5}} \end{array} \right\}.$$

Given enough events, the $\mu^+\nu_\mu$ mode is probably easier to detect because of its clean signature. In the ratio $\Gamma(B^+ \to \mu^+\nu_\mu)/\Delta m_d$, the factor $f_B$ cancels, leaving us with the
ratio $R^2 \equiv |V_{ub}/V_{td}|^2$. Contours of constant $R$ [31] are circles in the $(\rho, \eta)$ plane with centers $(\rho_0, \eta_0) = (R^2/[R^2 - 1], 0)$ and radii $R/|1 - R^2|$. For $(\rho, \eta) = (0, 0.36)$ a 10% measurement of $R^2$ (achievable with 100 observed $B^+ \to \mu^+\nu_\mu$ decays) gives $\eta$ to $\pm 0.02$. For $B(B^+ \to \mu^+\nu_\mu) = 2 \times 10^{-7}$ one then needs 500 million $B^+$, or about 500 million $B\bar{B}$ pairs produced at the $\Upsilon(4S)$.

IV. KAON INFORMATION

The parameter $\epsilon'/\epsilon$, a measure of direct CP violation, is probed in the double ratio

$$
\frac{\Gamma(K_L \to \pi^0\pi^0)}{\Gamma(K_S \to \pi^0\pi^0)} \times \frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^+\pi^-)} = 1 - 6 \text{ Re} \frac{\epsilon'}{\epsilon}.
$$

In principle $\epsilon'/\epsilon$ is proportional to $\eta$, though there are significant corrections due, for example, to electroweak penguins, and hadronic matrix elements are very uncertain. A likely range is $\epsilon'/\epsilon = (0-1) \times 10^{-3}$ [32]. If $\epsilon'/\epsilon \neq 0$ the superweak theory [20] will finally have been disproved.

The decay $K^+ \to \pi^+\nu\bar{\nu}$ is sensitive to loop processes, mainly to $V_{td}$ but also to a non-negligible charm contribution. Thus, it roughly measures the parameter $|1.4 - \rho - i\eta|$. The standard prediction [33] is $B(K^+ \to \pi^+\nu\bar{\nu}) \simeq 10^{-10} \times 2^{\pm 1}$. After a search of several years, Brookhaven Experiment E-787 has finally seen one event for this process [34], corresponding to a branching ratio of $(4.2^{+9.7}_{-3.5}) \times 10^{-10}$ or a limit $|1.4 - \rho - i\eta| > 0.7$. This still does not encroach upon the allowed region in Fig. 2, but more data are expected.

The process $K_L \to \pi^0e^+e^-$ is dominated by direct and indirect ($\sim \epsilon$) CP-violating contributions; there is also a small CP-conserving two-photon contribution [35]. The direct contribution is proportional to $i\eta$; the indirect contribution is expected to have comparable magnitude and the phase of $\epsilon$ (about $\pi/4$). This process may be background limited before the expected branching ratio ($< \mathcal{O}(10^{-11})$) is attained. An even more challenging process, but one which would provide valuable information on $\eta$, is $K_L \to \pi^0\nu\bar{\nu}$. The standard-model expectation for this branching ratio is $(2.8 \pm 1.7) \times 10^{-10}$ [36], more than 5 orders of magnitude below present upper limits [37].

V. CP VIOLATION IN B DECAYS

There is no simple analog to the $K_S$–$K_L$ system in neutral $B$ decays, Whereas the $K_S$ and $K_L$ differ in lifetime by a factor of 600, the lifetime differences for nonstrange $B$ mass eigenstates are expected to be negligible, and at most 10 or 20% for strange $B$’s [37]. However, in two major types of experiments, there should be substantial CP-violating asymmetries in $B$ decays. These are decays to CP eigenstates and “self-tagging” decays.

A. Decays to CP eigenstates. Clean measurements of angles in the unitarity triangle are possible when there is a single dominant amplitude for each process $B^0 \to f$ and $\bar{B}^0 \to f$, where $f$ is a CP eigenstate. Interference between the decay and $B^0$–$\bar{B}^0$ mixing amplitudes then leads to an a difference between the time-integrated rates $\Gamma(B^0 \to f)$ and $\Gamma(\bar{B}^0 \to f)$. When $f = J/\psi K_S$, the rate asymmetry is proportional to $\sin(2\beta)$ as
long as there is no additional source of $B\bar{B}$ mixing. When $f = \pi^+\pi^-$, the rate asymmetry is approximately proportional to $\sin(2\alpha)$ in the limit that penguin contributions can be neglected; in order to sort these out many techniques have been suggested, including an isospin analysis based on also detecting the $\pi^+\pi^0$ and $\pi^0\pi^0$ final states [33].

In decays to CP eigenstates the flavor of the decaying state at time of production must be identified by independent means, since the final state could have come from either $B$ or $\bar{B}$. We shall comment briefly on one aspect of progress in “tagging” the produced $B$ in Section VIII. In electron-positron collisions at the $\Upsilon(4S)$ the time-dependent asymmetry is odd in the difference between the decay times of the $B$ and $\bar{B}$, and would vanish upon integration over all times. One must thus resolve these two times, requiring either precise vertex discrimination or an asymmetric energy configuration. The former possibility is under consideration for the CESR machine [39], while the latter strategy is being employed in the construction of asymmetric $B$ “factories” at SLAC and KEK.

A nice way to pinpoint the angle $\beta$ from the rate asymmetries in $B \to J/\psi + X$ was mentioned at this Workshop [40]. If $X = K_S$, the rate asymmetry involves an interference between amplitudes proportional to $\cos \beta$ and ones proportional to $\sin \beta$, leading to an asymmetry $\sim \cos \beta \sin \beta \sim \sin(2\beta)$. There is considerable ambiguity in learning $\beta$ from $\sin(2\beta)$. However, if $X = \pi \ell \nu$ the interference term between $K_S$ and $K_L$ contributions to this final state (with lifetime dependence $e^{-\tau(\gamma_S+\gamma_L)\tau/2}$) contains a contribution $\sim \cos(2\beta)$, which is helpful in resolving this ambiguity. Since $\pi \ell \nu$ events are spread out over a kaon proper lifetime $\tau_K \leq \mathcal{O}(\tau_L) \simeq 600\tau_S$, the statistical power of the interference term is diluted with respect to the $\sin(2\beta)$ term by a factor of $\sim 1/300$, requiring high luminosity (which may well be available in second-generation experiments).

B. “Self-tagging” decays. Consider the decays $B \to f$ and $\bar{B} \to \bar{f}$, where $f$ and $\bar{f}$ are charge-conjugates of one another which can be distinguished experimentally. Suppose there are two decay amplitudes contributing to $B \to f$ and $\bar{B} \to \bar{f}$:

$$A(B \to f) = a_1 e^{i(\phi_1 + \delta_1)} + a_2 e^{i(\phi_2 + \delta_2)} , \quad A(\bar{B} \to \bar{f}) = a_1 e^{i(-\phi_1 + \delta_1)} + a_2 e^{i(-\phi_2 + \delta_2)} , \quad (9)$$

where $\phi_i$ are weak phases and $\delta_i$ are strong phases. Note that under charge conjugation, the weak phases change sign, whereas the strong phases do not. The rate asymmetry $A \equiv |\Gamma(f) - \Gamma(\bar{f})|/|\Gamma(f) + \Gamma(\bar{f})|$ is then proportional to $\sin(\phi_1 - \phi_2) \sin(\delta_1 - \delta_2)$, requiring nonzero weak and strong phases differences in order to be observed. Once this criterion is satisfied, it suffices to compare total rates (or branching ratios) for the processes $B \to f$ and $\bar{B} \to \bar{f}$. As we shall see in Section VI, one can sometimes learn about weak phases even in the absence of any observed CP-violating rate asymmetry.

VI. ASPECTS OF RATE MEASUREMENTS

A. Pocket guide to direct CP asymmetries. In the discussion of Sec. V B, let us suppose that both strong and weak phase differences are non-negligible, so that $\sin(\phi_1 - \phi_2) \sim \sin(\delta_1 - \delta_2) \sim \mathcal{O}(1)$. Then the rate asymmetry is

$$A = \mathcal{O}(\frac{a_1 a_2}{a_1^2 + a_2^2}) \sim \frac{a_2}{a_1} \sim \sqrt{\frac{N_2}{N_1}} \quad (10)$$
for $a_2 \ll a_1$. Here $N_i = \text{const}|a_i|^2$ is the rate associated with the amplitude $a_i$ acting independently. Now, the statistical error in the asymmetry is $\delta A \sim \mathcal{O}(N_i^{-1/2})$ (since one is detecting a total of about $N_i$ events). Hence the inverse fractional error on the asymmetry (the significance of the measurement, in standard deviations) is $A/\delta A \sim \mathcal{O}(N_i^{1/2})$. Thus, to see an asymmetry at a significant level one needs the rate from the rarer amplitude (here, $a_2$) to correspond to a significant signal.

To search for CP asymmetries in self-tagging $B$ decays one then looks for processes with (1) at least two contributing amplitudes, (2) a sufficiently large rate for the smaller amplitude, (3) a weak phase difference between the two amplitudes, and (4) a good chance for a strong phase difference between the two amplitudes. Although this last criterion may involve some luck, we shall indicate some likely prospects below.

**B. Interesting levels for charmless $B$ decays.** Current upper bounds on many branching ratios for charmless $B$ decays are a few times $10^{-5}$, whereas the likely levels for these processes are of order $10^{-5}$ [14]. These set the scale of the dominant amplitudes $a_1$ in charmless $B$ decays. The subdominant amplitudes $a_2$ are typically of order $\lambda a_1$, so the corresponding branching ratios are of order $\lambda^2 \times 10^{-5} \simeq 5 \times 10^{-7}$. Thus a factor of about 100 increase in data with respect to present samples would permit the study of interference between dominant and subdominant amplitudes in a whole host of charmless $B$ decays, assuming the most favorable strong phase difference $\delta_1 - \delta_2$. This same level also would permit one to learn weak phases from decay rates even if final state phase differences vanish, as noted in one example below.

**C. What amplitudes matter?** The above qualitative estimate is supported by analyses based on several amplitudes for which evidence already exists in charmless $B$ decays.

(1) The decays $B^0 \to K^+\pi^-$ and $B^+ \to K^0\pi^+$ have been observed [12] (here we do not distinguish between a process and its charge conjugate) with branching ratios

$$\mathcal{B}(B^0 \to K^+\pi^-) = (1.5^{+0.5}_{-0.4} \pm 0.1 \pm 0.1) \times 10^{-5} \quad (11)$$
$$\mathcal{B}(B^+ \to K^0\pi^+) = (2.3^{+1.1}_{-1.0} \pm 0.3 \pm 0.2) \times 10^{-5} \quad (12)$$

Both processes are expected to be dominated by a strangeness-changing ($\bar{b} \to \bar{s}$) penguin amplitude $P'$, so we average their branching ratios to obtain the estimate $|P'|^2 = (1.6 \pm 0.4) \times 10^{-5}$. Here and subsequently we express squares of amplitudes in units of $B$ branching ratios. Then since $P' \sim V_{ts} V_{ts}^*$ while the strangeness-preserving ($\bar{b} \to d$) penguin amplitude $P$ involves the corresponding factor $V_{tb} V_{td}$, we have $|P/P'| \simeq |V_{td}/V_{ts}| \simeq \lambda$. Thus one expects $|P|^2 \simeq \lambda^2 |P'|^2 \simeq |P'|^2/20 \simeq 8 \times 10^{-7}$.

(2) The decays $B^+ \to K^+\eta'$ and $B^0 \to K^0\eta'$ have been observed [13] with respective branching ratios of $(6.5^{+1.5}_{-1.4} \pm 0.9) \times 10^{-5}$ and $(4.7^{+2.7}_{-2.0} \pm 0.9) \times 10^{-5}$. Since these are likely to be dominated by an isospin-singlet transition, we average the two values to obtain $\mathcal{B}(B \to K \eta') = (5.9 \pm 1.4) \times 10^{-5}$. These processes are likely to receive an important contribution [14] from a $\bar{b} \to \bar{s}$ penguin process which contributes exclusively to flavor-singlet meson production, as illustrated in Fig. 3. Without the additional contribution of this graph, one would predict $\mathcal{B}(B \to K \eta') = (2.4 \pm 0.6) \times 10^{-5}$. Depending on the relative phase of the amplitudes $S'$ and $P'$, one will have $|S'|^2$ in the range of one
Figure 3: Example of graph contributing to amplitudes $S (q' = \bar{d})$ and $S' (q' = s)$, where $q_1 \bar{q}_1$ stands for a flavor-SU(3)-singlet meson.

Table 1: Dominant amplitudes, CKM combinations, and their expected phases in charmless $B$ decays.

| $\Delta S$ | Tree   | Penguin  |
|----------------|--------|----------|
| 0              | $V_{ub}^* V_{ud}$, $\gamma$ | $V_{tb}^* V_{td}$, $-\beta$ |
| 1              | $V_{ub}^* V_{us}$, $\gamma$ | $V_{tb}^* V_{ts}$, $\pi$ |

to several times $10^{-5}$. By reasoning similar to that for the estimate of $|P/P'|$, we then find $|S|^2 = O(5 \times 10^{-7})$.

(3) Although there is no significant evidence for either $B^0 \to \pi^+ \pi^-$ or $B^+ \to \pi^+ \pi^0$ so far, both are expected to be dominated by a “tree” ($T$) subprocess of the form $\bar{b} \to \bar{u}W^{++} \to \bar{u}u \bar{d}$, and averaging the expected contributions for the two processes using what meager data exist [12] we find [11] $|T|^2 \simeq 0.8 \times 10^{-5}$, an estimate which is consistent with the observed rate for $B \to \pi \ell \nu_\ell$ [13]. Then the corresponding strangeness-changing “tree” amplitude $T'$, describing the subprocess $\bar{b} \to \bar{u}W^{++} \to \bar{u}u \bar{s}$, has square $|T'|^2 \simeq \lambda^2|T|^2 \simeq 4 \times 10^{-7}$. (Flavor-SU(3) breaking is likely to multiply this estimate by a factor of $(f_K/f_\pi)^2 \simeq 1.5$.)

Thus, there are several pieces of evidence that when branching ratios of a few times $10^{-7}$ correspond to observable rates, one will be able to study the interference between dominant and subdominant amplitudes in a whole range of charmless $B$ decays.

D. Phases of amplitudes.

The amplitudes expected to dominate charmless $B$ decays are summarized briefly in Table 1. The “tree” amplitude is expected to dominate the $\Delta S = 0$ charmless $B$ decays such as $B^0 \to \pi^+ \pi^-$ through the combination $V_{ub}^* V_{ud}$, while the “penguin” amplitude is expected to dominate the $|\Delta S| = 1$ charmless $B$ decays such as $B^0 \to K^+ \pi^-$ through the combination $V_{tb}^* V_{td}$ or possibly $V_{tb}^* V_{ts}$. The relative phase of the tree and penguin amplitudes in the $\Delta S = 0$ decays is $\gamma + \beta = \pi - \alpha$, while that in the $|\Delta S| = 1$ processes is just $\gamma$. By studying a combination of $B^0 \to \pi^+ \pi^-$, $B^0 \to K^+ \pi^-$, $B^+ \to K^0 \pi^+$, and their charge-conjugates, one can learn $\alpha$, $\gamma$, and the relative strong phases of tree and penguin amplitudes [40].
E. Flavor SU(3): An application to decays with $\eta$, $\eta'$. Flavor SU(3) may be used in conjunction with the amplitudes discussed in Sec. VI C to identify processes for which there is a good chance of seeing large effects of direct CP violation. One is looking for processes which involve two amplitudes of comparable strength. The decays $B^\pm \to \pi^\pm \eta$ and $B^\pm \to \pi^\pm \eta'$ turn out to be likely candidates.

We performed a flavor-SU(3) decomposition of decays of $B$ mesons to two light pseudoscalar mesons $^{11}$, including contributions from electroweak penguin terms $^{10}$. We neglected all annihilation- and exchange-type amplitudes, which are expected to be highly suppressed in comparison with those considered. We calculated expected squares of contributions of individual amplitudes to decays, ignoring for present purposes any interference between tree ($t$, $t'$) and other amplitudes. We considered two possibilities for the relative phase of the two predominant amplitudes, $p'$ and $s'$, in the decay $B^+ \to K^+ \eta'$, corresponding to constructive interference and no interference between these amplitudes. (The amplitudes denoted by small letters are are related to those with large letters in Sec. VI C by the inclusion of small electroweak penguin contributions.)

We found that the branching ratios for $B^+ \to \pi^+ \eta$ due to the $|t|^2$, $|p|^2$ contributions acting alone are $(2.8, 1) \times 10^{-6}$, within a factor of 3 of one another. Aside from small electroweak penguin corrections, the weak phases of $t$ and $p$ amplitudes are expected to differ by $\alpha$ (mod $\pi$) as noted in Table 1. Thus, if the strong phases also differ appreciably, there is a good chance for a sizeable rate difference between $B^+ \to \pi^+ \eta$ and $B^- \to \pi^- \eta$.

A similarly optimistic conclusion may be drawn for $B^\pm \to \pi^\pm \eta'$. The $|t|^2$ contribution to the branching ratio was found to be $1.4 \times 10^{-6}$, with the $|s|^2$ contribution of the same order. The relative weak phase of the two amplitudes is again $\alpha$ (mod $\pi$), while if the $|s|^2$ contribution is due to rescattering or other long-distance effects $^{51}$ the relative strong phase could be appreciable.

F. $B \to$ Vector ($V$) + Pseudoscalar ($P$) decays. The CLEO Collaboration $^{52}$ has now observed the decays $B^+ \to \omega \pi^+$ and $B \to \omega K^+$ with branching ratios of $(1.1^{+0.6}_{-0.5} \pm 0.2) \times 10^{-5}$ (2.9$\sigma$) and $(1.5^{+0.7}_{-0.6} \pm 0.3) \times 10^{-5}$ (4.3$\sigma$), respectively. These are the first reported decays of $B$ mesons to charmless final states involving a vector ($V$) and a pseudoscalar ($P$) meson. $VP$ final states may be crucial in studies of CP violation in $B$ decays $^{14}$.

In Ref. $^{53}$ we used flavor SU(3) and the observed decays to anticipate the observability of other charmless $B \to VP$ decays in the near future. We identified amplitudes in the flavor-SU(3) decomposition likely to be large as a result of present evidence. These consist of a strangeness-preserving “tree” amplitude $t_V$ and a strangeness-changing penguin amplitude $p'_V$. In both cases the subscript indicates that the spectator quark is incorporated into a vector ($V$) meson. Other decays depending on the amplitude $t_V$ are $B^+ \to \rho^0 \pi^+$ and $B^0 \to \rho^- \pi^+$. If $t_V$ is the dominant amplitude in these processes, we expect $\Gamma(B^+ \to \rho^0 \pi^+) = \Gamma(B^+ \to \omega \pi^+)$ and $\Gamma(B^0 \to \rho^- \pi^+) = 2\Gamma(B^+ \to \omega \pi^+)$. Furthermore, model calculations predicting $|t_P| > |t_V|$ imply that decays expected to be dominated by $t_P$, such as $B^+ \to \rho^+ \pi^0$ and $B^0 \to \rho^+ \pi^-$, will also have branching ratios in excess of $10^{-5}$.

An appreciable value for the amplitude $p'_V$, somewhat of a surprise in conventional
models [54], implies that $B \to \rho K$ decays should be observable at branching ratio levels in excess of $10^{-5}$. The smallness of the ratio $B(B^+ \to \phi K^+)/B(B^+ \to \omega K^+)$ indicates that $|p'_\rho| < |p'_\omega|$. The amplitude $p'_\rho$ should dominate not only $B \to \phi K$ but also $B \to K^+\pi$ decays. Evidence for any of these would then tell us the magnitude of $p'_\rho$. The relative phase of $p'_\rho$ and $p'_\omega$ is probed by $B \to K^*(\eta, \eta')$ decays.

Once the dominant amplitudes have been determined, flavor SU(3) predicts the remaining tree and penguin amplitudes. One can then (cf. Ref. [41]) determine which processes are likely to exhibit noticeable interferences between two or more amplitudes, thereby having the potential for displaying direct CP-violating asymmetries. These asymmetries should be visible once one has attained about a factor of 100 increase in data over present samples: a factor of 5 to reach the expected $\mathcal{O}(10^{-5})$ branching ratios for dominant amplitudes, and a further factor of $\lambda^{-2} \simeq 20$ to see the subdominant rates (as in Secs. VI A and B).

**G. Statistical requirements for determining $\gamma$ in $B^\pm \to DK^{\pm}$ decays.** Gronau and Wyler [55] have pointed out that one can measure the angle $\gamma$ if one measures the rates for $B^+ \to D^0K^+, B^+ \to \bar{D}^0K^+, B^+ \to D^{0}_{CP}K^+$ (where $D^{0}_{CP}$ is a CP eigenstate), and the corresponding charge-conjugate processes. (Atwood, Dunietz, and Soni [56] have noted that this method requires one to take account of interference between CKM-favored and doubly suppressed decays of the neutral charmed meson.) The rarest of these decays is the color-suppressed $B^+ \to D^0K^+$, whose branching ratio is probably a few $\times 10^{-6}$, or [57] $(\lambda/3)^2$ times that of the color-suppressed process $B^+ \to J/\psi K^+$, whose branching ratio is about $10^{-3}$ [7]. With an effective 10% detection efficiency for $D^0$ one is again at an effective branching ratio of a few times $10^{-7}$, as in the charmless $B$ decays mentioned earlier.

**H. Measuring $\gamma$ in $B \to K \pi$.** The decay $B^+ \to K^0\pi^+$ is expected to be dominated by the $\bar{b} \to \bar{s}$ penguin amplitude in the limit that rescattering (or annihilation) contributions can be neglected [13]. In this case, which we assume, the rates for $B^+ \to K^0\pi^+$ and $B^- \to K^0\pi^-$ should be equal. Other tests for the presence of rescattering effects have been proposed [13].

The decays $B^0 \to K^+\pi^-$ and $\bar{B}^0 \to K^-\pi^+$, on the other hand, are dominated by the penguin amplitude but should receive some contribution from the tree subprocess as well. One then forms the ratio

$$ R \equiv \frac{\Gamma(K^+\pi^-) + \Gamma(K^-\pi^+)}{\Gamma(K^0\pi^+) + \Gamma(K^0\pi^-)} = 1 - 2r \cos \gamma \cos \delta + r^2 \quad , \quad (13) $$

where $r \equiv |T'/P'|$ and $\delta$ is a strong phase difference between the penguin and tree amplitudes [20, 21, 22]. Fleischer and Mannel [21] have pointed out that if $R < 1$, a useful bound $\sin^2 \gamma < R$ holds for any $r$ and $\delta$. At present $R = 0.65 \pm 0.40$ [42], so the central value of $R$ is indeed below 1, but no conclusion can be reached yet.

If the ratio $r$ is known, one can do better [53]. One can combine the above ratio with the CP-violating rate “pseudo-asymmetry”

$$ A_0 \equiv \frac{\Gamma(B^0 \to K^+\pi^-) - \Gamma(\bar{B}^0 \to K^-\pi^+)}{\Gamma(B^+ \to K^0\pi^+) + \Gamma(B^- \to K^0\pi^-)} \quad , \quad (14) $$
to find an expression for $\gamma$ which depends only on these quantities and on the ratio $r$, for which we provide an estimate based on $B \rightarrow \pi\pi$ and $B \rightarrow \pi\ell\nu\ell$ decays. A similar idea can be applied to $B_s \rightarrow K^+K^-$ and $B_s \rightarrow K^0\bar{K}^0$ decays [62, 64].

In Fig. 4 we plot contours of fixed asymmetry $|A_0|$ in the $\gamma - R$ plane. (Note that one cannot distinguish between $\gamma$ and $\pi - \gamma$ using this method since when $\gamma \rightarrow \pi - \gamma, \delta \rightarrow \pi - \delta$ both $R$ and $A_0$ are unchanged.) The case $r = 0.16$ is shown; for other values see Ref. [58]. Present data imply errors on $r$ of $\pm 0.06$, about a factor of 4 too large to permit a useful determination of $\gamma$. Assuming $r$ is sufficiently well known, that $45^\circ < \gamma < 135^\circ$, that rescattering effects and electroweak penguins are negligible (they may not be; see Ref. [58] for details), a measurement of $\gamma$ to $\pm 10^\circ$ requires $R$ to be known to $\pm 0.028$, or a data sample of about 200 times the present one [12] of 3.3 million $B\bar{B}$ pairs. The determination of $\gamma$ to $\pm 10^\circ$ and $\eta$ to $\pm 0.02$ (mentioned in Sec. III D) can significantly restrict the range of parameters in Fig. 2.

VII. CHARM-ANTICHARM ANNIHILATION

A number of features of $B$ decays look just enough out of line with respect to theoretical expectations to be worth a raised eyebrow.
1. The semileptonic branching ratio $\mathcal{B}(B \to X\ell\nu)$ is about 11% (vs. a theoretical prediction of about 12%) \[12\].

2. The number $n_c$ of charmed particles per average $B$ decay is about 1.1 to 1.2 vs. a theoretical prediction of 1.2 to 1.3 \[12\].

3. The inclusive branching ratio $\mathcal{B}(B \to \eta'X)$ appears large \[43\] in comparison with theoretical expectations \[65\].

4. The exclusive branching ratio $\mathcal{B}(B \to K\eta')$ appears to require an additional contribution (as illustrated in the example of Fig. 3) in comparison with the penguin contribution leading to $B^0 \to K^+\pi^-$ or $B^+ \to K^0\pi^+$. A common source for these effects could be an enhanced rate for the subprocess $\bar{b} \to \bar{c}c\bar{s}$, where $q$ stands for a light quark \[66\], e.g., through rescattering effects. These are inherently long-range and nonperturbative and could also be responsible for the overall enhancement of the $\bar{b} \to \bar{s}$ penguin transitions noted in Refs. \[51\]. Alternatives for points (3) and (4) which have been suggested include a large $c\bar{c}$ \[67\] or gluonic component in the $\eta'$. The former possibility is intriguing but one must then ascribe the suppression of the decay $J/\psi \to \eta'\gamma$ to form factor effects. A large gluonic admixture in the $\eta'$ would depress the predicted branching ratio $\mathcal{B}(\phi \to \eta'\gamma)$ below the value of about $10^{-4}$ predicted \[68\] if $\eta'$ is mainly a $q\bar{q}$ state. At this Workshop I have learned that the CMD-2 Detector at VEPP-2 in Novosibirsk has presented the first evidence (6 events) for the long-sought $\phi \to \eta'\gamma$ decay \[69\], with a branching ratio consistent with the standard prediction.

If rescattering from the $\bar{b} \to \bar{c}c\bar{s}$ subprocess into states containing light quarks really is important, both the penguin amplitude $P'$ and the singlet penguin $S'$ mentioned in Sec. VI C could have strong phases very different from the tree amplitude $T'$, raising the possibility of substantial CP-violating asymmetries whenever these amplitudes interfere with one another in a self-tagging $B$ decay (such as $B^0 \to K^+\pi^-$).

VIII. TAGGING REMARKS

A. Same-side tagging. Several years ago a method was proposed for identifying the flavor of a neutral $B$ at the time of production by means of correlations with the charge of the pion produced nearby in phase space \[70\]. There has been considerable progress in utilizing this method, originally at LEP \[71\] but more recently by the CDF Collaboration \[72\]. The idea is simple, and is even incorporated into existing Monte Carlo fragmentation programs: A produced $\bar{b}$, when fragmenting into a $B^0$, requires production of a $d$ quark, so that a $\bar{d}$ quark is the next quark down the rapidity chain. If this quark is incorporated into a charged pion, that pion must be a $\pi^+$. Thus, one expects a correlation between $\pi^+$ and $B^0$, and, correspondingly, between $\pi^-$ and $\bar{B}^0$.

If the fragmentation of a leading $b$ or $\bar{b}$ quark takes place in a charge-independent manner, one should expect the $B^+\pi^-$ correlation to be the same as the $B^0\pi^+$ correlation, by isospin reflection. This is not what CDF sees; the $B^+\pi^-$ correlation tends to be stronger. Several reasons for this have been noted \[73\]. One instrumental effect against
which one must guard is the misidentification of charged kaons as charged pions. A correlation is expected between charged \( B \)'s and oppositely charged kaons, but not between neutral \( B \)'s and charged kaons.

B. Importance of resonances. The \( B^0 \pi^+ \) and \( \bar{B}^0 \pi^- \) correlations mentioned above are just those expected from resonance decays. Now, decays of narrow resonances can lead to a considerable improvement of the signal-to-noise ratio in studying such correlations. In the case of charm, the vector meson decays \( D^*+ \rightarrow D^0 \pi^+ \) and \( D^*- \rightarrow \bar{D}^0 \pi^- \) have been crucial in identifying neutral \( D \)'s, since the pions are almost at rest with respect to them. The corresponding \( B^* \) vector mesons lie too close in mass to the \( B \)'s for a strong decay. One must look to the next excited states, consisting of a \( b \) and a light antiquark (\( \bar{q} \)) in a P-wave.

There are two known P-wave \( c\bar{q} \) resonances \( \mathcal{J} \): the \( D_2^*(2460) \) and the \( D_1(2420) \), where the subscript stands for the total angular momentum \( J \). These decay via D-wave final states: \( D_2^* \rightarrow [(D \text{ or } D^*) \pi]_{\ell=2} \), \( D_1 \rightarrow [D^* \pi]_{\ell=2} \) and hence are fairly narrow. Candidates for the corresponding \( B_2^* \) states have been seen \( \mathcal{J} \). Such states should be useful in tagging neutral \( B \)'s, as has been emphasized in Refs. \( \mathcal{J} \).

One is still missing two predicted P-wave resonances in both the \( c\bar{q} \) and \( b\bar{q} \) systems. One, with \( J = 1 \), should decay to \( [(D \text{ or } B^*) \pi]_{\ell=0} \), while the other, with \( J = 0 \), should decay to \( [(D \text{ or } B) \pi]_{\ell=0} \). These could in part be responsible for the observed correlations, since they are expected to be broad (being able to decay via S-waves) and hence difficult to distinguish from nonresonant effects.

IX. EFFECTS BEYOND THE STANDARD MODEL

A. Loop-dominated \( B \) decays. Table 2 summarizes some \( B \) decay processes which are dominated by loop diagrams. The theoretical numbers are taken from the indicated references or from a recent review by Ali \( \mathcal{J} \). The experimental results are from Refs. \( \mathcal{J} \). New particles in loops can include supersymmetric partners, extra Higgs bosons, new quarks, new \( q\bar{q}t\bar{t} \) interactions, and much more \( \mathcal{J} \).

In the standard model, the loop diagrams affecting \( b \rightarrow s \gamma \) involve an intermediate \( u,c,t \) and an intermediate \( W^- \). These also contribute to \( b \rightarrow s\ell^+\ell^- \), with the \( \ell^+\ell^- \) pair produced by a virtual photon or \( Z \). However, the process \( b \rightarrow s\ell^+\ell^- \) also receives a contribution from a box diagram with an intermediate \( W^+W^- \) pair. Thus, non-standard physics can affect \( b \rightarrow s \gamma \) and \( b \rightarrow s\ell^+\ell^- \) in different ways. The ratio of rates for these two processes, the \( m_{\ell^+\ell^-} \) spectrum, and the energy distributions of the leptons are all tools which can be used to distinguish among non-standard models.

B. Supersymmetry. Loop diagrams can contain not only superpartners, but also additional Higgs bosons. A 25\% comparison between theory and experiment can lead to significant restrictions on the parameter space \( \mathcal{J} \).

C. Technicolor-like interactions. There may be new higher-dimension \( \bar{b}s\bar{t}t \) interactions which, when integrated over the \( tt \) loop, contribute to \( b \rightarrow s \gamma \). There can also be
rate asymmetry in which new physics can show up in decay amplitudes. One compares the decay $B \to \bar{s}\ell^+\ell^-$ and $b \to s\nu\bar{\nu}$. The latter may be correlated with modifications to $K \to \pi\nu\bar{\nu}$ rates [83].

**D. New quark families.** The invisible decays of the $Z$ indicate that there are only three families of light neutrinos with standard electroweak couplings. However, the possibility still remains open of additional families of quarks and leptons if the corresponding neutrinos are sufficiently heavy, or of exotic quarks beyond the standard left-handed doublets $(u, d), (c, s), (t, b)$. Thus, one can have modifications of $V_{ts}$ and $V_{td}$; more $Q = 2/3$ quarks in loops, or even anomalous $t\bar{t}\gamma$ and $t\bar{t}Z$ couplings. All these can affect $b \to s\gamma$ and $b \to s\ell^+\ell^-$ processes.

**E. New Higgs bosons.** Supersymmetry and non-supersymmetric grand unified theories beyond SU(5) both predict an extended Higgs boson sector, with charged Higgs bosons that can participate in loop diagrams. Since these bosons in general couple differently than $W^\pm$, they can affect the relative rates of $b \to s\gamma$ and $b \to s\ell^+\ell^-$, and the kinematic variables in the latter.

**F. $B \to \phi K_S$ and new physics.** A very pretty observation [83] illustrates a way in which new physics can show up in decay amplitudes. One compares the decay $B^0 \to \phi K_S$, which is expected to be dominated by the $\bar{s}$ penguin amplitude (with weak phase $\pi$) with the decay $B^0 \to J/\psi K_S$, which is expected to be dominated by the subprocess $b \to c\bar{c}s\bar{s}$, with weak phase 0. The CP-violating asymmetry in both these decays arise from the interference of the decay amplitude with the $B^0 - \bar{B}^0$ mixing amplitude (whose weak phase is $2\beta$). Thus the standard model predicts a time-integrated rate asymmetry

$$\frac{\Gamma(B^0 \to \phi K_S) - \Gamma(\bar{B}^0 \to \phi K_S)}{\Gamma(B^0 \to \phi K_S) + \Gamma(\bar{B}^0 \to \phi K_S)} = \frac{\Gamma(B^0 \to J/\psi K_S) - \Gamma(\bar{B}^0 \to J/\psi K_S)}{\Gamma(B^0 \to J/\psi K_S) + \Gamma(\bar{B}^0 \to J/\psi K_S)} = -\frac{x \sin(2\beta)}{1 + x^2}$$

where $x \equiv |\Delta m/G|_{B^0} \simeq 0.7$. New physics in the penguin amplitude can change the weak phase in $B^0 \to \phi K^0$, so that the asymmetries in $\phi K_S$ and $J/\psi K_S$ are no longer equal.

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**Table 2: Decays of nonstrange $B$ mesons dominated by loop diagrams.**

| Decay Mode | Experimental limit or rate | Branching ratio in standard model |
|------------|---------------------------|----------------------------------|
| $\mu^+\mu^-$ | $< 6.9 \times 10^{-9}$ | $1.1 \times 10^{-10}$ |
| $\gamma\gamma$ | $< 3.9 \times 10^{-5}$ | $10^{-8}$ |
| $X_{\gamma\gamma}$ | $(2.32 \pm 0.57 \pm 0.35) \times 10^{-4}$ | $(3.25 \pm 0.30 \pm 0.40) \times 10^{-4}$ |
| $X_{\mu^+\mu^-}$ | $< 4.7 \times 10^{-5}$ | $(5.73^{+0.75}_{-0.78}) \times 10^{-6}$ |
| $K^0(e^+e^-/\mu^+\mu^-)$ | $(1.5/2.6) \times 10^{-4}$ | $(5 \pm 3/3 \pm 1.8) \times 10^{-7}$ |
| $K^+(e^+e^-/\mu^+\mu^-)$ | $(1.2/0.9) \times 10^{-4}$ | $(5 \pm 3/3 \pm 1.8) \times 10^{-7}$ |

$a$ CDF [76]. $b$ Rate $\sim m_\ell^2$ for small lepton mass $m_\ell$. $c$ L3 [77]. $d$ CLEO [78]. $e$ ALEPH [74]. $f$ Scale, $m_\nu$ error. $g$ Ref. [80]. $h$ CLEO [81], $\ell^+\ell^-$. $i$ CLEO [81].
Standard sources in fact can lead to a difference between the two asymmetries of at most a few %; differences in excess of this figure are considered interesting \cite{83}. The absence of an anomalously high $B^+ \rightarrow \phi \pi^+$ rate (the current branching ratio upper limit \cite{12} is $B < 5 \times 10^{-6}$) and an upper bound on $\mathcal{B}(B^+ \rightarrow \bar{K}^* 0 K^+)$ are useful in bounding any anomalously high contribution of the $u \bar{u}$ loop in the $\bar{b} \rightarrow \bar{s}$ penguin diagram.

X. SUMMARY

A. What lies ahead? (1) Are the CKM matrix and its phases the source of CP violation for $K_L$ and $K_S$? If so, we may see a deviation in the double ratio \cite{84} from unity. (2) Do $B$ decays provide a consistent set of CKM phases? If so, there are definite predictions for the time-integrated rate asymmetry in the $J/\psi K_S$ final state. Progress has been made in “tagging” neutral $B$’s, necessary to identify this asymmetry. One expects many checks of the CKM predictions in measurements of decay rates of charged and neutral $B$’s.

A ratio of exactly 1 for \cite{84} unfortunately lies within the allowed parameter space for the CKM theory. However, the potential for discrepancies with respect to the CKM theory is very great in measurements using $B$ mesons. If such discrepancies are found, one will have to explore other sources of CP violation, such as superweak models, right-handed $W$’s, multi-Higgs models, and supersymmetry. A generic feature of these last three is the prediction of electron and neutron electric dipole moments \cite{86} not far below present limits; the CKM theory predicts values well below these and probably inaccessible to foreseeable experiments.

B. Quark and lepton families. Another possibility for experiments with $B$’s is that they will fail to expose any inconsistencies in the CKM picture. This will sharpen the question of where the CKM phases really originate; we do not understand that any better than we understand quark and lepton masses. Such an understanding is far overdue and is not provided by any theories currently on the market. The pattern of quark and lepton masses and couplings (see, e.g., Ref. \cite{4}) is strongly reminiscent of a level structure, with intensity rules favoring nearest-neighbor transitions as in atomic physics or quarkonium \cite{87}.

C. Favorite nonstandard model. For one example of physics beyond the standard model one can look to grand unified groups beyond SU(5) and SO(10), such as $E_6$ (see, e.g, Ref. \cite{88}). Each family of quarks and leptons belongs to a reducible $5^* + 10$ multiplet of SU(5), which becomes a $16$-spinor of SO(10) [= $5^* + 10 + 1$ of SU(5)] when a right-handed neutrino is added. The Higgs boson naturally belongs to a vector $10$ representation of SO(10), which in supersymmetry would be accompanied by a $10$ of fermions. The simplest representation containing both a $16$ and a $10$ of fermions, once we add a further $1$ of fermions, is the $27$-plet of $E_6$. Now, if we like, we can throw away the supersymmetry and simply consider the properties of matter in the $27$-plet. The $10$-plet of SO(10) decomposes into a $5 + 5^*$ of SU(5), consisting of the following left-handed particles and their charge-conjugates: (1) an isoscalar, color-triplet quark $h$; (2) a vector-like charged lepton $E^+$, and (3) the corresponding (anti)neutrino $\nu_E$. The $1$ of SO(10) is a sterile left-handed neutrino. Each $16$-plet family of quarks and leptons is
accompanied by a 10 and a 1. The ordinary quarks $d, s, b$ of charge $-1/3$ can mix with the three different $h$’s, leading to a variety of flavor-changing neutral currents. Thus, the unitarity triangle may not close, with interesting consequences for experiments with $B$ mesons \[89\].

D. Demonstrations and conclusions. I close with two demonstrations. The first (see \[4\]) is one you may want to try on audiences who have not heard it before; show them a block of 8 by 4 squares and ask them if they recognize the pattern. Then separate the block into two pieces, with 2 columns of 4 squares on the left and 6 columns of 4 on the right, and ask again. Finally fill in the missing squares – hydrogen, helium, and the transition metals – to form the periodic table of the elements. Most people will recognize it by this point; the variety of the pattern usually is the key. A few individuals see the pattern immediately.

The second uses an asymmetric top \[90\] whose principal axes of inertia are not aligned with the axis with which it makes contact with the surface on which it is placed. As a result, it can spin in one direction freely, but if it is set spinning in the other direction, it will gradually slow down and then reverse its direction. Question: what symmetries are violated? Answer: P and T. T violation in particle physics is likely to be more subtle!

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