Rare and Semileptonic Decays of B and K Mesons

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Abstract. I describe the goals, challenges, and recent advances in studies of rare and semileptonic decays of B and K mesons. There are now many rare flavor-changing-neutral-current processes under study; these modes provide sensitivity to amplitudes arising from new physics. Progress has also been made on measuring the magnitudes of several Cabibbo-Kobayashi-Maskawa matrix elements, and we focus particular attention on V_{us}, V_{td}, V_{cb}, and V_{ub}. The quark masses m_b and m_c have been determined surprisingly well from inclusive B decays. Many of these studies rely on a detailed understanding of how strong interactions affect the underlying weak decay, and we examine how such effects are controlled.

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INTRODUCTION

I am delighted to present an overview of recent progress on rare and semileptonic decays of B and K mesons. These decays encompass a wide range of processes that allow us to measure Standard Model (SM) parameters such as Cabibbo-Kobayashi-Maskawa matrix (CKM) elements and quark masses, to search for the effects of new physics using intriguing electroweak penguin decays, and to perform surprisingly detailed studies of the effects of strong interactions on the underlying weak decay.

My discussion of rare decays will focus on processes whose final states include photons or leptons in addition to the daughter hadron(s). Examples include the electromagnetic or electroweak penguin decays $B \to K^*\gamma$, $B \to \rho\gamma$, $B \to K^{(*)}\ell^+\ell^-$, and $K_L^0 \to \pi^0\nu\bar{\nu}$, as well as the leptonic decays $B_s \to \mu^+\mu^-$ and $B \to \ell^+\ell^-$. The restriction to at least partly electromagnetic or leptonic final states implies that theoretical predictions for the decay rates can in some cases be rather precise, permitting quantitative comparison with experiment. Many of the most interesting rare decays have diagrams with internal loops or boxes leading to effective flavor-changing neutral current (FCNC) transitions. These processes can be very sensitive to new physics at high mass scales. Of course, FCNC transitions can also produce purely hadronic final states. Here, however, the decay rates are very difficult to predict due to more complicated strong-interaction effects, including final-state interactions between the daughter hadrons. The tremendous importance of hadronic final states derives from the possibilities for interference between amplitudes with different CP-violating phases, which can lead to CP-violating asymmetries. (Such measurements are discussed in the talks by Kazuo Abe and Hassan Jawahery.) Studies using radiative/leptonic/semileptonic and hadronic final states are therefore comple-

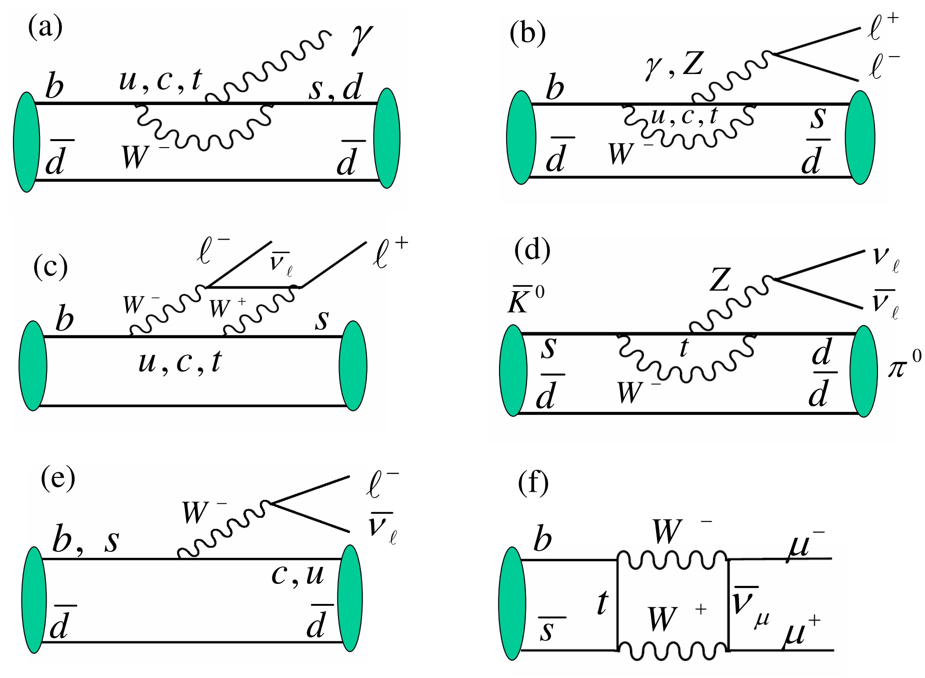

FIGURE 1. Diagrams for a selection of rare and semileptonic B and K decays.

mentary: the first approach restricts the type of final-state particles to gain control over strong-interaction effects; the second focuses on CP asymmetries, for which the strong-interaction matrix elements sometimes divide out.

The second major subject of my talk is the progress in the venerable but nevertheless quite lively area of semileptonic decays. Here again, a key feature is that reliable calculations can be performed, providing a way to extract the magnitudes of CKM matrix elements from the measured decay rates. In addition to progress in the determination of several CKM elements, there have been two recent surprises in this field: the so-called "kaon revolution," in which the branching fractions of several kaon decays have been significantly revised, and the remarkably precise determinations of the b- and c-quark masses, which have emerged from detailed studies of decay distributions of inclusive semileptonic and radiative-penguin decays of B mesons.

Figure 1 shows examples of diagrams for rare, semileptonic, and leptonic decays of B and K mesons. Figure 2 shows some examples of ways in which new particles (SUSY partners, charged Higgs) can enter the loop in $b \to s$ transitions. Because these diagrams occur at the same order in perturbation theory as the SM amplitude, the sensitivity to new physics is potentially quite large.

A common theme of these studies is the need to understand the dynamics of the decay process. The underlying short-distance interactions responsible for the weak decay are

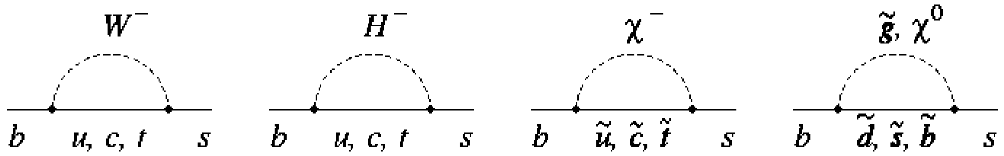

FIGURE 2. Contributions to the $b \to s$ transition from the SM and non-SM amplitudes.

usually straightforward to calculate; however, the situation is complicated by an overlay of strong-interaction effects, some of which are non-perturbative. Fortunately, the amplitudes for the processes we consider factorize into the product of two currents, only one of which is hadronic. The effects of the strong interactions in exclusive processes can then be rigorously parametrized in terms of form factors or a decay constant. For inclusive B decays, the amplitudes for such processes can expressed in terms of Operator Product Expansions that exploit the relatively large value of the b- and c-quark masses. In these explansions, nonperturbative QCD effects can also be parametrized in a well-defined manner.

The isolation of strong-interaction effects into well-defined quantities is critical. In some cases, this implies that theoretical methods such as lattice QCD can be used to compute the non-perturbative quantity. In others, the required information can be extracted from the rates for other closely related processes, or from measurements of kinematic distributions such as lepton, photon, or hadron momentum spectra. We will see examples of the impressive progress and insights gained from this approach, and some of the promising pathways for the future.

The B and K decays discussed here provide information on the magnitudes of five of the nine CKM matrix elements: V_{us}, V_{ub}, V_{cb}, V_{td}, and V_{ts}. The CKM matrix [1] for three quark generations contains only four independent, real parameters and can be written in the Wolfenstein parametrization [2] in terms of the quantities A, λ, ρ, and η:

$$\begin{aligned}
\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} &= \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathscr{O}(\lambda^4) \\
&\approx \begin{pmatrix} 0.97 & 0.23 & 0.004 \\ -0.23 & 0.97 & 0.04 \\ 0.008 & -0.04 & 1 \end{pmatrix}.
\end{aligned} \tag{1}$$

(The numerical values given in the last line leave out the phases.) Both K and B decays are CKM suppressed, because in each case, the s or b quark must decay outside of its own generation. This requirement, which creates a certain degree of commonality in K and B physics, introduces a factor V_{us}, V_{cb}, or another small CKM element in the amplitude. We also see that, although V_{cb} is shifted off the diagonal by one unit (the same as V_{us}), it is suppressed by an additional factor of λ, the sine of the Cabibbo angle. The complex quantities in the CKM matrix (whose location is dependent on phase convention) are the source of CP violation in the SM. The CKM matrix predicts a broad range of phenomena in which both CP-conserving and CP-violating observables are tied together into a single unified framework.

THE SEARCH FOR $K_L^0 \to \pi^0 \nu \bar{\nu}$

The decay $K_L^0 \to \pi^0 \nu \bar{\nu}$ occupies a special place among the most challenging processes to measure. Like Mt. Everest, it has a compelling quality because of this extreme difficulty. At the same time, $K_L^0 \to \pi^0 \nu \bar{\nu}$ offers direct access to a key quantity of the CKM matrix that is related to CP violation, the parameter η in Eq. 1.

In the SM, the decay $K_L^0 \to \pi^0 \nu \bar{\nu}$ proceeds either through a Z penguin (Fig. 1d) or a W^+W^- box diagram (similar to Fig. 1c), giving rise to a dominantly $s \to t \to d$ transition and introducing the factor

$$V_{ts} V_{td}^* = (-A\lambda^2) \cdot (A\lambda^3) \cdot (1 - \rho + i\eta). \tag{2}$$

This would not be as interesting if we were starting with a K^0 or $\bar{K}^0$ flavor eigenstate, but experiments can also search for the decay $K_L^0 \to \pi^0 \nu \bar{\nu}$. The K_L^0 is a superposition of K^0 and $\bar{K}^0$, so the relevant amplitude is

$$Amp(K_L^0 \to \pi^0 \nu \bar{\nu}) \propto (V_{ts}^* V_{td} - V_{ts} V_{td}^*) \propto A^2 \lambda^5 \eta. \tag{3}$$

The decay therefore provides an essentially direct measurement of η, the imaginary part of V_{ub} and V_{td}.

The expected SM branching fraction, however, is only $\mathscr{B}(K_L^0 \to \pi^0 \nu \bar{\nu}) = (3.0 \pm 0.6) \times 10^{-11}$ [3], so an enormous data sample would be required to observe the decay. (The hadronic current used in the calculation of this matrix element is determined from the decay $K^+ \to \pi^0 e^+ \nu$, exploiting the factorizable nature of the amplitude.) It is worth noting that the related rare decay $K^+ \to \pi^+ \nu \bar{\nu}$ was observed by the Brookhaven E787 experiment and the follow-on experiment E949 [4] with a total of only 3 signal events. The branching fraction measured with the combined data sample is $\mathscr{B}(K^+ \to \pi^+ \nu \bar{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10}$, slightly higher than the SM prediction $(7.8 \pm 1.2) \times 10^{-11}$ [3]. This success demonstrates that an extremely rare process can be identified with a specially designed experiment.

The experimental challenge of $K_L^0 \to \pi^0 \nu \bar{\nu}$ is not just the tiny branching fraction. The observable final state contains only a π^0, which recoils against a significant amount of missing transverse momentum associated with the two neutrinos. A dedicated experiment, KEK E391a in Japan, has presented preliminary results from an early data sample [5]. In E391a, a collimated K_L^0 "pencil beam" a few cm across is created with typical momentum of 3 GeV. The nearly hermetic detector has a highly efficient CsI calorimeter system, which is critical for vetoing enormous backgrounds from $K_L^0 \to \pi^0 \pi^0$ and $n + X \to \pi^0 + Y$. Because the decay position of the K_L^0 is not known, one cannot reconstuct a π^0 mass peak from the measured photon energies in the calorimeter. Instead, the π^0 mass hypothesis is imposed, and the decay vertex position along the beam direction (z) is reconstructed. The signal box is then a region in the z-p_T plane, where p_T is the transverse momentum of the candidate π^0.

E391a has so far analyzed only a small part of its data sample, achieving a limit of $\mathscr{B}(K_L^0 \to \pi^0 \nu \bar{\nu}) < 2.86 \times 10^{-7}$ (90% C.L.). They hope to reach a limit of 1.4×10^{-9}. A proposal is in preparation for a follow-on experiment at J-PARC to reach a sensitivity that would allow observation and measurement of the decay.

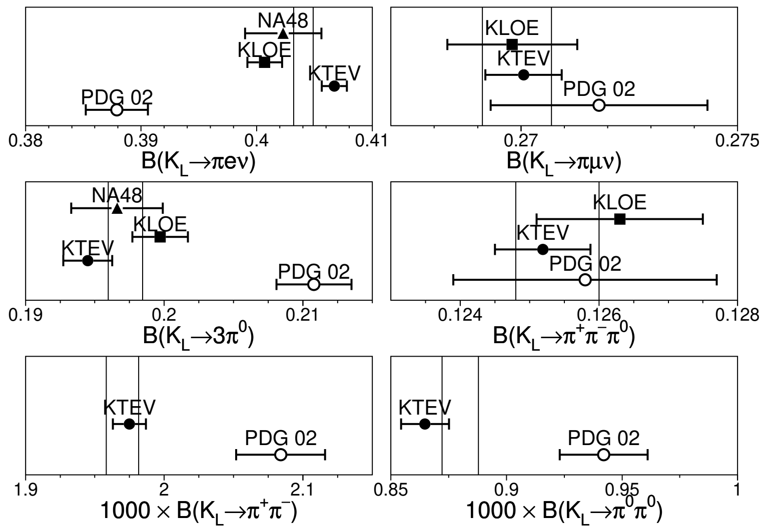

FIGURE 3. Summary and global fit to recent results on K_L^0 branching fractions. (Figure courtesy of Ed Blucher.)

$K \to \pi e \nu$, $|V_{us}|$, AND THE "KAON REVOLUTION"

Although many years of effort have been invested in the kaon system, there have been some surprising results affecting several branching fractions considered to be well established. If we return to the 2002 edition of the *Review of Particle Properties* [6], we would find that the departure from unitarity in the first row of the CKM matrix is

$$1-(|V_{ud}|^2-|V_{us}|^2-|V_{ub}|^2)=(0.0043\pm0.0019), \tag{4}$$

where the values used were $|V_{ud}|=0.9734\pm0.0008$ and $|V_{us}|=0.2196\pm0.0026$. ($|V_{ub}|$ is so small that it can be neglected for present purposes.) The extraction of $|V_{us}|$ from the $K\to\pi e\nu$ or $K\to\pi\mu\nu$ decay rates (computed from the branching fractions and lifetime) requires significant theoretical input, as we can see from the expression [7]

$$\Gamma_{K\ell 3}=\frac{G_F^2 M_K^5}{192\pi^3}|V_{us}|^2\cdot S_{EW}(1+\delta_K^\ell+\delta_{SU2})C^2\cdot f_+^2(q^2=0)\cdot I_K^\ell, \tag{5}$$

where S_{EW} [8] gives short distance radiative corrections, the δ_K^ℓ give long distance radiative corrections [9], δ_{SU2} gives I-spin corrections for K^+ decay, $C^2=1$ for K_L^0 and $C^2=\frac{1}{2}$ for K^+ decay, $f_+(0)$ is the form factor [10] at $q^2=0$, and I_K^ℓ is obtained by integrating the shape of the squared form factor over phase space. The shape of the form factor is obtained from experiment.

The recalibration of K_L^0 branching fractions is based on results from several experiments, including KTeV, NA48, and KLOE. KTeV measured the six largest K_L^0 modes, which together account for 99.93% of the rate, and it has also remeasured the semileptonic form factors [11]. Since the decays are not tagged, the observed yields are expressed as five ratios of branching fractions, which essentially sum to unity. The data

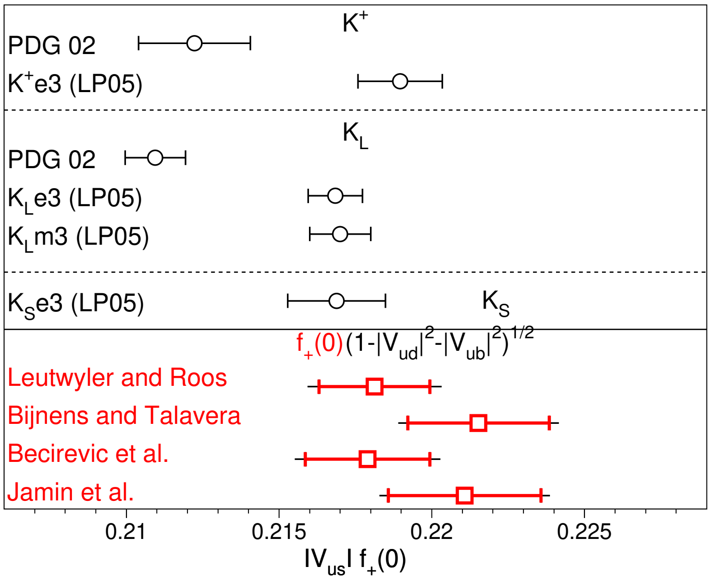

FIGURE 4. Compilation of $V_{us}f_+(0)$ determinations using global fits to recent measurements kaon decays. The lower portion of the figure shows values of $|V_{us}|f_+(0)$ obtained by assuming unitarity of the first row of the CKM matrix. (Figure courtesy of Ed Blucher.)

samples are very large, with 10^5-10^6 events per mode. Careful treatment of radiation from electrons was an important element of the analysis and may have been a problem in earlier measurements.

The branching fractions from the KTeV analysis, as well as those from KLOE and NA48, are compared with the PDG02 values in Fig. 3. Significant shifts with respect to previous world averages are observed in several modes, including $K_L^0 \to \pi^\pm e^\mp \nu$, $K_L^0 \to \pi^+\pi^-$, $K_L^0 \to \pi^0\pi^0$, and $K_L^0 \to \pi^0\pi^0\pi^0$. The effect of these results on the extraction of $|V_{us}|$ is shown in Fig. 4, which summarizes values of $|V_{us}f_+(0)|$ from experiment (in the upper section) and from the CKM matrix under the assumption of unitarity (in the lower section). The averages were performed by Ed Blucher [7], and include results from KLOE, KTeV, NA48, and ISTRA+. Using $f_+(0) = 0.961 \pm 0.008$, the average value of $|V_{us}f_+(0)| = 0.2173 \pm 0.0008$ yields $|V_{us}| = 0.2261 \pm 0.0021$. This “cures” the unitarity problem for the first row of the CKM matrix, but with further measurements of $|V_{ud}|$ and some possible theoretical refinements both underway, the question of unitarity remains open.

Given the complexity of these measurements and the related theoretical calculations, it is desirable to have a crosscheck of $|V_{us}|$ based on an independent method. One can also extract $|V_{us}|$ from the ratio of the kaon to pion leptonic decay rates:

$$\frac{\Gamma(K^+ \to \mu^+ \nu)}{\Gamma(\pi^+ \to \mu^+ \nu)} = \frac{|V_{us}|^2}{|V_{ud}|^2} \frac{f_K^2}{f_\pi^2} \frac{m_K^2 - m_\mu^2}{m_\pi^2 - m_\mu^2} \left[1 - \frac{\alpha}{\pi}(C_\pi - C_K)\right], \tag{6}$$

where the values of C_π and C_K are given by Marciano [12] and the ratio of f_K/K_π is obtained from lattice QCD [13]. Using data from the KLOE experiment [14], this method leads to $|V_{us}| = 0.2223 \pm 0.0026$, consistent with the results from semileptonic

K decay but not quite as precise. Further checks and refinements of both methods will be very valuable.

RADIATIVE PENGUIN DECAYS OF B MESONS

The discovery of the decay $B \to K^*\gamma$ in 1993 by the CLEO II experiment [15] provided the first clear evidence for loop processes in B decays, in this case radiative penguins (Fig. 1a). The branching fraction $\mathscr{B}(B \to K^*\gamma) \approx 4 \times 10^{-5}$, while small, is large enough that many thousands of these events are now observed in the B-factory data samples, which contain hundreds of millions of $\Upsilon(4S) \to B\bar{B}$ decays. The study of radiative penguins has blossomed into a physics program with roughly 20 $B \to X_s\gamma$ or $B \to X_d\gamma$ exclusive decay modes now observed [16]. Radiative penguin processes are absent in K decays because the photon must recoil against a spin-1 (or higher) daughter hadron to conserve angular momentum, and the kaon is not sufficiently heavy for this to occur.

A very recent development in the study of radiative penguin decays is the observation by Belle [17] of the process $B \to \rho\gamma$, which is the first a $b \to d\gamma$ transition to be observed. From the rate for $B \to \rho\gamma$ relative to $B \to K^*\gamma$, one can constrain $|V_{td}|$ using [18]

$$\frac{\mathscr{B}(B \to (\rho,\omega)\gamma)}{\mathscr{B}(B \to K^*\gamma)} = \left|\frac{V_{td}}{V_{ts}}\right|^2 \frac{(1-m^2_{(\rho,\omega)}/m_B^2)^3}{(1-m^2_{K^*}/m_B^2)^3}\zeta^2(1+\Delta R),$$

where $\Delta R = 0.1 \pm 0.1$ and $\zeta = 0.85 \pm 0.10$. Using a sample of 386 M $B\bar{B}$ pairs, Belle observes 8.2 events in $B^- \to \rho^-\gamma$, 20.8 events in $\bar{B}^0 \to \rho^0\gamma$, and 5.9 events in $\bar{B}^0 \to \omega\gamma$, for a combined significance of 5.5σ. From the average branching fraction over these three related modes, one can extract $|V_{td}/V_{ts}| = 0.200^{+0.026+0.038}_{-0.025-0.029}$. BaBar, however, with a sample of 211 M $B\bar{B}$ events, does not observe a significant signal, and obtains limits on the branching fraction [19]. There is some controversy in the $B^0 \to \rho^0\gamma$ channel, where Belle obtains $\mathscr{B}(B^0 \to \rho^0\gamma) = (1.17^{+0.35+0.09}_{-0.31-0.08}) \times 10^{-6}$, indicating an I-spin violation relative to $B^- \to \rho^-\gamma$. BaBar obtains the limit $\mathscr{B}(B^0 \to \rho^0\gamma) < 0.4 \times 10^{-6}$ (90 % C.L.).

The inclusive $b \to s\gamma$ process $\mathscr{B}(B \to X_s\gamma)$ provides a canonical method for testing the SM at one-loop level. The theoretical predictions are more reliable than those for exclusive decays, and great effort has been invested in calculating the QCD and electroweak corrections to this decay rate. One such prediction is [20]

$$\mathscr{B}(B \to X_s\gamma) = (3.61^{+0.24}_{-0.40}|_{m_c/m_b} \pm 0.02|_{CKM} \pm 0.24|_{param} \pm 0.14|_{scale}) \times 10^{-4}, \tag{7}$$

for $E_\gamma > 1.6$ GeV, which is consistent with the current experimental average [16] $\mathscr{B}(B \to X_s\gamma) = (3.39^{+0.30}_{-0.27}) \times 10^{-4}$. Measuring the inclusive decay rate is difficult because one has either to ignore the X_s system, thereby summing over it, or to reconstruct the many possible X_s systems that can be produced. The first approach [21] is called the "fully inclusive" method; it is in some sense ideal, but suffers more from backgrounds, especially non-$B\bar{B}$ continuum processes. In the second approach [22], one tries to reconstruct as many possible final states as possible and then sum over them. The background rejection is better, but there is more model dependence from assumptions about non-reconstructed modes. The second approach, however, has provided valuable

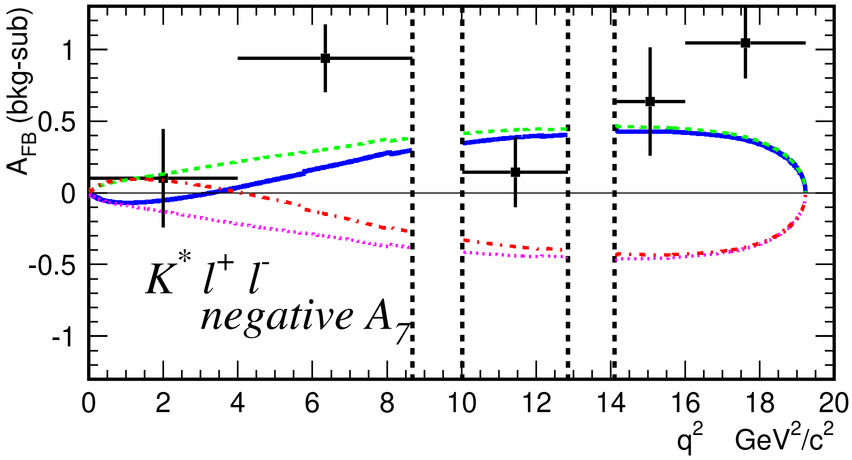

FIGURE 5. Preliminary Belle measurement of the lepton forward-backward asymmetry A_{FB} in $B \to K^* \ell^+ \ell^-$ as a function of q^2. The points with error bars are the data, and the SM prediction is shown as a solid curve. Various new physics scenarios are shown as dotted curves.

information on the photon-energy spectrum. The moments of this spectrum have been used [23] to extract information on the b-quark mass.

ELECTROWEAK PENGUINS $B \to K\ell^+\ell^-$ AND $B \to K^*\ell^+\ell^-$

Studies of penguin processes have been extended even further to include the decays $B \to K\ell^+\ell^-$, $B \to K^*\ell^+\ell^-$, and the inclusive process $B \to X_s\ell^+\ell^-$. These decays involve not only the photon-penguin diagram, but also a Z-penguin and a box diagram involving two W bosons (Figs. 1b, c), which dominate over much of phase space. (The photon penguin dominates at very low dilepton masses.) Significant signals have been observed by both BaBar [24] and Belle [25], and the world-average values [16] for the branching fractions are $\mathscr{B}(B \to K\ell^+\ell^-) = (0.45 \pm 0.05) \times 10^{-6}$ and $\mathscr{B}(B \to K^*\ell^+\ell^-) = (1.18 \pm 0.17) \times 10^{-6}$. The $B \to K\ell^+\ell^-$ mode is the rarest B decay so far observed.

While these results are in reasonable agreement with predictions based on the SM, as are measurements of the inclusive decay $B \to X_s\ell^+\ell^-$, there is a potentially more powerful method to search for new physics using kinematic distributions. In particular, one can measure the forward-backward asymmetry (A_{FB}) of the leptons in the dilepton rest frame (for a specific B flavor and lepton charge); for the mode $B \to K^*\ell^+\ell^-$ this asymmetry contains a great deal of information about the short-distance physics. In the SM, A_{FB} has a distinctive behavior as a function of q^2 (the mass squared of the dilepton system), and it can be substantially affected by the presence of new physics, which can even flip the sign of A_{FB}. The SM also predicts that $A_{FB}(q^2)$ must be zero at a well-defined value of q^2. Present data are limited, but first studies of the asymmetry function $A_{FB}(q^2)$ give a sign of A_{FB} that is consistent with the SM. Figure 5 shows $A_{FB}(q^2)$ in the Belle data [25]. This measurement will be pursued for many years as the data samples increase, both at the e^+e^- B factories and at the LHC.

PRECISION MEASUREMENT OF $|V_{cb}|$ AND THE "ATOMIC PHYSICS" OF B MESONS

The precision measurement of $|V_{cb}|$ has been a long-term goal in heavy-quark physics, requiring the joint effort of the experimental and theoretical communities. Remarkably, this goal appears to have been achieved, with the uncertainty on $|V_{cb}|$ now at the 2% level. The value of $|V_{cb}|$ is used in the calculation of $|V_{ub}/V_{cb}| = \sqrt{\rho^2+\eta^2}$, a key constraint in the $\rho - \eta$ plane (an annular region when uncertainties are included). It also determines the quantity A in the Wolfenstein parametrization, so $|V_{cb}|$ effectively enters into K-decay predictions involving $|V_{ts}|$, such as Eq. 3.

Experiment and theory have used two main approaches, both of which require detailed studies of kinematic distributions, not just the measurement of overall decay rates. The first method involves measurement of the exclusive decay $B \to D^* \ell^- \bar{\nu}$ for the kinematic configuration in which the D^* is produced nearly at rest, thus selecting $b \to c$ transitions that minimally disturb the rest of the meson. The second method uses the inclusive semileptonic process $B \to X_c \ell^- \bar{\nu}$, as well as information from the inclusive radiative-penguin decay $B \to X_s \gamma$, which helps to constrain the b-quark mass.

The high-precision measurement of $|V_{cb}|$ using either method requires control of nonperturbative QCD effects. The inclusive rate also depends on the famous factor m_b^5 typical of low-energy weak decays, as well as on the factor $(m_c/m_b)^2$. The $B \to X_c \ell^- \bar{\nu}$ decay provides three main observables that are used in the extraction of $|V_{cb}|$, the quark masses, and QCD parameters characterizing the bound-state ("atomic") physics of the B meson. These observables are the inclusive semileptonic rate, the inclusive lepton-energy spectrum, and the inclusive recoil hadron mass spectrum. In practice, certain moments of the spectra are used as the observables. From all of these quantities, a joint fit is performed from which one can extract not only $|V_{cb}|$, but also m_b, m_c, and four nonperturbative QCD parameters: μ_G (the chromomagnetic expectation value), μ_π (kinetic energy expectation value), ρ_D (Darwin term), and ρ_{LS} (spin-orbit coupling) [26]. The BaBar data yield values for all of these quantities [27]; a partial list is

$$\begin{aligned}
|V_{cb}| &= (41.4 \pm 0.4_{\rm exp} \pm 0.4_{\rm HQE} \pm 0.6_{\rm th}) \times 10^{-3} \\
\mathscr{B}(B \to X_c \ell \nu) &= (10.61 \pm 0.16_{\rm exp} \pm 0.06_{\rm HQE})\% \\
m_b &= (4.61 \pm 0.05_{\rm exp} \pm 0.04_{\rm HQE} \pm 0.02_{\alpha_s})\ \mathrm{GeV} \\
m_c &= (1.18 \pm 0.07_{\rm exp} \pm 0.06_{\rm HQE} \pm 0.02_{\alpha_s})\ \mathrm{GeV} \\
\mu_\pi^2 &= (0.45 \pm 0.04_{\rm exp} \pm 0.04_{\rm HQE} \pm 0.01_{\alpha_s})\ \mathrm{GeV}^2 \\
\mu_G^2 &= (0.27 \pm 0.06_{\rm exp} \pm 0.03_{\rm HQE} \pm 0.02_{\alpha_s})\ \mathrm{GeV}^2 \qquad (8)
\end{aligned}$$

The masses and QCD parameters are quoted in the "kinetic scheme," but they can be converted into other schemes as well.

A combined fit to BaBar, Belle, CDF, CLEO, and DELPHI data has been performed [28] using both the semileptonic data and the $B \to X_s \gamma$ inclusive photon spectrum, which has good sensitivity to the b-quark mass. The results of this fit are

$$|V_{cb}| = (41.58 \pm 0.45 \pm 0.58) \times 10^{-3} \qquad m_b = 4.591 \pm 0.040\ \mathrm{GeV} \qquad (9)$$

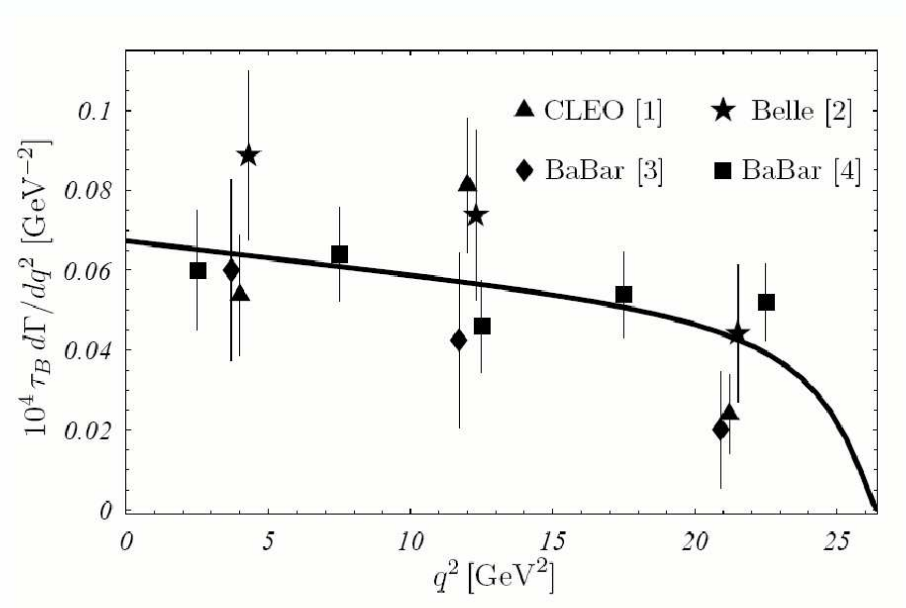

FIGURE 6. Data on the q^2 distribution for the decay $B \to \pi\ell^-\bar{\nu}$ from BaBar, Belle, and CLEO. The extraction of $|V_{ub}|$ is based on the high-q^2 region ($q^2 > 16$ GeV^2), where lattice QCD calculations are most reliable. (Compiled by Becker and Hill.)

The precision on these quantities is remarkable, especially on the b-quark mass, which is determined to better than 1%. The value of $|V_{cb}|$ quoted above agrees well with the world-average value [29] for the exclusive $B \to D^*\ell^-\bar{\nu}$ method: $|V_{cb}| = (40.9 \pm 1.0^{+1.6}_{-1.3}) \times 10^{-3}$. Further improvement on the latter measurement is desirable, so that it becomes a stronger cross-check.

MEASUREMENT OF $|V_{ub}|$

An intensive effort is underway [30] to improve the precision on $|V_{ub}|$, one of the smallest elements of the CKM matrix. Progess has been more difficult than for $|V_{cb}|$, since $|V_{ub}/V_{cb}| \approx 0.1$ and $\Gamma(B \to X_u\ell^-\bar{\nu})/\Gamma(B \to X_u\ell^-\bar{\nu}) \approx 2\%$. Measurements must contend with large backgrounds from $B \to X_c\ell^-\bar{\nu}$ processes, and truly inclusive measurements are quite challenging. Some progress has been made by using a technique in which one B meson in an $\Upsilon(4S) \to B\bar{B}$ event is fully reconstructed; this method results in a loss of statistical precision but provides powerful background rejection and useful kinematic constraints. Measurements of the decay rate in the lepton-endpoint region, where $B \to X_c\ell^-\bar{\nu}$ background is much reduced, are also useful. The uncertainties from individual inclusive measurements are now in the 10% range, and the Heavy Flavor Averaging Group [16] quotes a world average value

$$|V_{ub}| = (4.38 \pm 0.19 \pm 0.27) \times 10^{-3}, \tag{10}$$

where the first uncertainty is experimental and the second is from m_b and theory. Some caution is advisable here, since the systematic errors are large, and their probability content is not well defined. Eventually, it may be possible to push the total error down to the 5%-7% range. An alternative method that appears to have great promise is the measurement of the $B \to \pi\ell^-\bar{\nu}$ rate as a function of q^2. Figure 6 shows data from BaBar, Belle, and CLEO, as compiled by Becher and Hill [31]. Lattice calculations [32] for the rate in the high q^2 region have been performed and should be substantially refined in the future. We need both inclusive and exclusive measurements to provide a crosscheck on this extremely important quantity.

SEARCH FOR $B_s \to \mu^+\mu^-$ AND $B^0 \to \ell^+\ell^-$

Purely leptonic decays of B mesons are rare processes and have not yet been observed. The decays $B^0 \to \ell^+\ell^-$ and $B_s \to \mu^+\mu^-$ are highly suppressed in the SM; for example, the SM predicts $\mathscr{B}(B_s \to \mu^+\mu^-) = (3.5 \pm 0.9) \times 10^{-9}$. The expected rates are too small to be observed at the Tevatron or B factories, but these decays are still interesting because they can receive very large enhancements from new physics. CDF and D0 have set the limits [33] $\mathscr{B}(B_s \to \mu^+\mu^-) < 1.6 \times 10^{-7}$ and $\mathscr{B}(B_s \to \mu^+\mu^-) < 3.0 \times 10^{-7}$, respectively. BaBar and Belle have set limits [34] $\mathscr{B}(B^0 \to \mu^+\mu^-) < 8.3 \times 10^{-8}$ and $\mathscr{B}(B^0 \to \mu^+\mu^-) < 1.6 \times 10^{-7}$, with similar results for the electron mode. The constraints on SUSY models from the $B_s \to \mu^+\mu^-$ limits are relevant to the neutralino-proton cross section in mSUGRA [35], an intriguing connection between heavy-quark physics and cosmology.

PERSPECTIVE AND CONCLUSIONS

Important advances are being made in the field of rare and semileptonic decays of B and K mesons. The increasing sophistication of methods has led to precision measurements of CKM elements and quark masses, and the maturing of experimental methods has led to some revision of previous results. Studies of the rare decays, both FCNC and $b \to u$ transitions, still have great potential to teach us new things. With the planned large increases in the B-factory data samples, I expect considerable progress to be made by the time of the next PANIC conference in three years.

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