Branching Ratios of B Mesons to K^+, K^-, and $K^0/\bar{K}^0$

M. S. Alam,[1] N. Katayama,[1] I. J. Kim,[1] C. R. Sun,[1] V. Tanikella,[1] D. Bortoletto,[2] A. Chen,[2] M. Goldberg,[2] R. Holmes,[2] N. Horwitz,[2] A. Jawahery,[2] P. Lubrano,[2] G. C. Moneti,[2] V. Sharma,[2] P. Thoma,[2] S. E. Csorna,[3] M. D. Mestayer,[3] R. S. Panvini,[3] G. B. Word,[3] A. Bean,[4] G. J. Bobbink,[4] I. C. Brock,[4] A. Engler,[4] T. Ferguson,[4] R. W. Kraemer,[4] C. Rippich,[4] H. Vogel,[4] C. Bebek,[5] K. Berkelman,[5] E. Blucher,[5] D. G. Cassel,[5] T. Copie,[5] R. DeSalvo,[5] J. W. DeWire,[5] R. Ehrlich,[5] R. S. Galik,[5] M. G. D. Gilchriese,[5] B. Gittelman,[5] S. W. Gray,[5] A. M. Halling,[5] D. L. Hartill,[5] B. K. Heltsley,[5] S. Holzner,[5] M. Ito,[5] J. Kandaswamy,[5] R. Kowalewski,[5] D. L. Kreinick,[5] Y. Kubota,[5] N. B. Mistry,[5] J. Mueller,[5] R. Namjoshi,[5] E. Nordberg,[5] M. Ogg,[5] D. Perticone,[5] D. Peterson,[5] M. Pisharody,[5] K. Read,[5] D. Riley,[5] A. Silverman,[5] S. Stone,[5] A. J. Sadoff,[6] P. Avery,[7] D. Besson,[7] L. Garren,[7] T. Bowcock,[8] R. T. Giles,[8] K. Kinoshita,[8] F. M. Pipkin,[8] Richard Wilson,[8] J. Wolinski,[8] D. Xiao,[8] T. Gentile,[9] P. Haas,[9] M. Hempstead,[9] T. Jensen,[9] H. Kagan,[9] R. Kass,[9] S. Behrends,[10] Jan M. Guida,[10] Joan A. Guida,[10] F. Morrow,[10] R. Poling,[10] E. H. Thorndike,[10] and P. Tipton[10]

[1] *State University of New York at Albany, Albany, New York 12222*
[2] *Syracuse University, Syracuse, New York 13210*
[3] *Vanderbilt University, Nashville, Tennessee 37235*
[4] *Carnegie Mellon University, Pittsburgh, Pennsylvania 15213*
[5] *Cornell University, Ithaca, New York 14853*
[6] *Ithaca College, Ithaca, New York 14850*
[7] *University of Florida, Gainesville, Florida 32611*
[8] *Harvard University, Cambridge, Massachusetts 02138*
[9] *Ohio State University, Columbus, Ohio 43210*
[10] *University of Rochester, Rochester, New York 14627*

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By studying lepton-kaon angular correlations in $\Upsilon(4S)$ decays, we have measured the branching ratios for $\bar{B}\to K^+X$, $\bar{B}\to K^-X$, $\bar{B}\to K^0/\bar{K}^0X$, $\bar{B}\to l^-K^+X$, $\bar{B}\to l^-K^-X$, and $\bar{B}\to l^-K^0/\bar{K}^0X$. Their values imply that $(b\to c)/(b\to \text{all})=0.98\pm0.16\pm0.12$.

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The decay of the b quark, the heaviest quark whose existence has been firmly established, is a natural testing ground for theories of the weak interaction. The standard model[1] holds that the b quark decays by mixing with lighter charge $-1/3$ quarks, d and s, as prescribed by the Kobayashi-Maskawa mixing matrix. The elements of this matrix are not predicted by the theory, and must be determined experimentally. The b quark can mix into the second generation (one step down) and decay into a c quark, or it can mix into the first generation (two steps down) and decay into a u quark. A central goal of b-decay studies is to determine the relative magnitudes of the decay widths $\Gamma(b\to uW^-)$ and $\Gamma(b\to cW^-)$.

Techniques which have previously been employed for this determination include studies of the B-meson semileptonic-decay momentum spectrum[2] and direct measurement of charmed-particle yields.[3] These measurements are hampered by significant systematic uncertainties, and the importance of the Kobayashi-Maskawa-angle determinations makes it essential to obtain as many independent measurements as possible.

One such independent approach is provided by the study of strange-particle production in B-meson decays. The c quark is known to decay dominantly into the s quark. Therefore, the decay chain $b\to cW^-$ followed by $c\to sW^+$ [Fig. 1(a)] should produce an excess of s quarks over $\bar{s}$ quarks. In contrast, the process $b\to uW^-$ [Fig. 1(b)] should produce s and $\bar{s}$ equally. Thus, measurement of any excess of s over $\bar{s}$ can provide a clear, quantitative signal for $b\to c$ production.

Previous measurements[4] of kaon yields in B decay have summed over s and $\bar{s}$ quarks. Here we separately measure $\bar{B}\to K^-X$ and $\bar{B}\to K^+X$. More explicitly, we present first measurements of the branching ratios

$$\frac{\Gamma(\bar{B}\to l^-K^-X)}{\Gamma(\bar{B}\to l^-X)},\quad \frac{\Gamma(\bar{B}\to l^-K^+X)}{\Gamma(\bar{B}\to l^-X)},\quad \frac{\Gamma(\bar{B}\to K^-X)}{\Gamma(\bar{B}\to \text{all})},\quad \frac{\Gamma(\bar{B}\to K^+X)}{\Gamma(\bar{B}\to \text{all})},\quad \frac{\Gamma(\bar{B}\to l^-K^0/\bar{K}^0X)}{\Gamma(\bar{B}\to l^-X)},$$

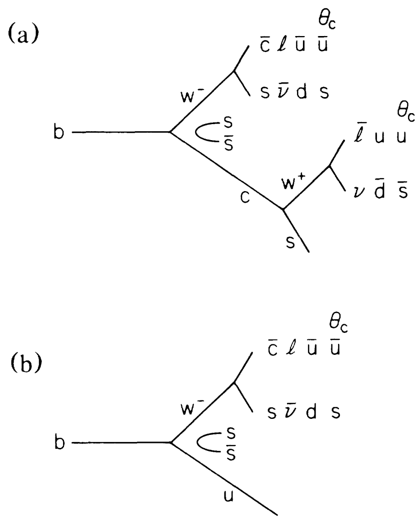

FIG. 1. Quark-level diagrams for the decay of the b quark, showing all sources of strange and antistrange quarks for (a) $b \to c$ and (b) $b \to u$. Cabibbo-suppressed decays are marked by θ_C.

and an improved measurement of the branching ratio

$$\frac{\Gamma(\bar{B} \to K^0/\bar{K}^0 X)}{\Gamma(\bar{B} \to \text{all})}.$$

Here, and throughout this Letter, we average over charge-conjugate states.

The B mesons used for this study were produced in the process $\Upsilon(4S) \to B\bar{B}$. Since the Q value of that decay is only 21 MeV,[5] the B and $\bar{B}$ are nearly at rest and their decay products are completely intermixed. We have used two-particle correlations to distinguish between the kaons from B and the kaons from $\bar{B}$. For example, in an event in which the $\bar{B}$ decays semileptonically, producing a negatively charged high-momentum lepton, conservation of momentum dictates that the other decay products from the $\bar{B}$ recoil against the lepton, with a probability distribution peaked at an angle 180° away from the lepton. The charge of the lepton tags the flavor of its parent B. Since B and $\bar{B}$ are spin 0 and are essentially at rest, the decay products from the B will be uncorrelated in direction with the lepton from the $\bar{B}$, and therefore distributed isotropically with respect to it. By fitting the distribution of included angle between lepton and like-charged kaon, lepton and oppositely charged kaon, and lepton and $K^0/\bar{K}^0$ with an isotropic component and a component peaked at 180°, we separately obtain the numbers of K^-, K^+, and $K^0/\bar{K}^0$ per semileptonic $\bar{B}$ decay and per average B decay.

This study was performed with the CLEO detector[6] at the Cornell Electron Storage Ring (CESR). The data sample consisted of 78 pb^{-1} on $\Upsilon(4S)$ and 36 pb^{-1} at energies just below $\Upsilon(4S)$. Events were required to satisfy our hadronic-event criteria[7] and to have at least five charged tracks. The central region of the CLEO detector contains a seventeen-layer cylindrical drift chamber instrumented to measure the specific ionization (dE/dx) of charged particles. We use these dE/dx capabilities to identify charged kaons in the momentum interval from 0.2 to 0.6 GeV/c. We determined the shape of the charged-kaon identification efficiency as a function of momentum by comparing measured charged and neutral-kaon yields, both from $\Upsilon(4S)$ decay and from the continuum. We assume that the neutral-kaon efficiency is well simulated by our Monte Carlo program and that the event generator correctly simulates the small differences between the neutral- and charged-kaon momentum spectra. We obtained the magnitude of the charged-kaon efficiency from a sample of $\phi \to K^+K^-$ events, comparing the yield of doubly identified pairs to the yield of singly identified pairs. The efficiency so obtained agrees well with an independent determination, based on Monte Carlo simulation of the dE/dx information.

Neutral kaons are detected[6] through their decay mode $K_S^0 \to \pi^+\pi^-$. We require an oppositely charged drift-chamber track pair with a momentum vector extrapolating back to the region of the event vertex. In addition, the pair must not be consistent with $\gamma \to e^+e^-$ or $\Lambda \to p\pi$. We use the wings of the $\pi^+\pi^-$ mass plot to determine the background.

Electrons were identified[2] by specific-ionization and electromagnetic-shower measurements. Muons were identified[2] by their ability to pass through 0.5–1.0 m of steel and be detected by both planes of the outer muon drift-chamber system. The leptons used in this study had momenta between 1.5 and 2.8 GeV/c. The requirement that the lepton momentum be greater than 1.5 GeV/c minimizes the number of leptons from D decay. There are 3770 ± 103 muons and 3230 ± 92 electrons from B decay in our event sample.

The distributions of included angle θ_{lK} for like-charged pairs and for oppositely charged pairs are shown in Figs. 2(a) and 2(b), respectively. Subtractions have been performed which use data collected just below the $\Upsilon(4S)$ to remove the 17% of all lepton-kaon pairs which are from continuum events. We estimate that 3% of the apparent leptons are misidentified hadrons,[2] and statistically subtract these pairs as well. We also subtract a Monte Carlo prediction of lepton-kaon pairs which include a particle misidentified as a $K^\pm$. Misidentifications account for $(13 \pm 1)\%$ of the observed yield of charged kaons. The distribution of $l^\pm K_S^0$ included angle is shown in Fig. 2(c). The distributions have not been corrected for kaon or lepton identification efficiencies. One notes a strong peak at 180° in the $l^\pm K^\pm$ plot and the $l^\pm K_S^0$ plot, and almost no peak and a larger isotropic component in the $l^\pm K^\mp$ plot. Since the process $b \to c \to s$ will produce like-charged pairs

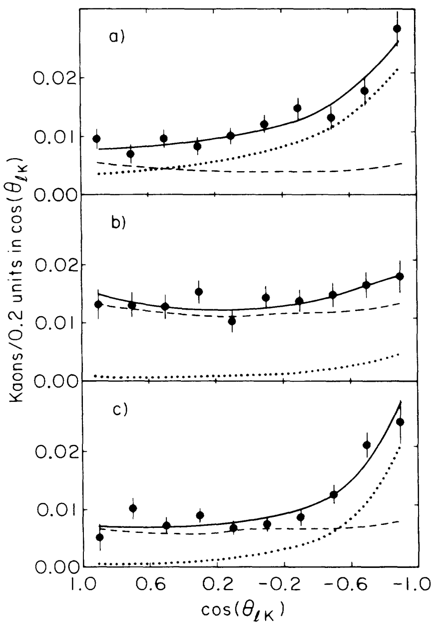

FIG. 2. Distribution of the included angle for (a) $l^{\pm}K^{\pm}$, (b) $l^{\pm}K^{\mp}$, and (c) $l^{\pm}K_S^0$. The distributions are normalized so as to be per identified lepton. The curves are from a $b \rightarrow c$ Monte Carlo simulation, scaled to give the best fit to the data. The dotted curve is for pairs from the same B, the dashed curve for pairs one from each B, and the solid curve their sum.

TABLE I. Branching ratios as measured by our fits. The errors shown are statistical and systematic, respectively.

Branching ratio	Measured value
$\frac{\Gamma(\bar{B} \rightarrow l^- K^- X)}{\Gamma(\bar{B} \rightarrow l^- X)}$	$0.54 \pm 0.07 \pm 0.06$
$\frac{\Gamma(\bar{B} \rightarrow l^- K^+ X)}{\Gamma(\bar{B} \rightarrow l^- X)}$	$0.10 \pm 0.05 \pm 0.02$
$\frac{\Gamma(\bar{B} \rightarrow l^- K^0/\bar{K}^0 X)}{\Gamma(\bar{B} \rightarrow l^- X)}$	$0.39 \pm 0.06 \pm 0.04$
$\frac{\Gamma(\bar{B} \rightarrow K^- X)}{\Gamma(\bar{B} \rightarrow \text{all})}$	$0.66 \pm 0.05 \pm 0.07$
$\frac{\Gamma(\bar{B} \rightarrow K^+ X)}{\Gamma(\bar{B} \rightarrow \text{all})}$	$0.19 \pm 0.05 \pm 0.02$
$\frac{\Gamma(\bar{B} \rightarrow K^0/\bar{K}^0 X)}{\Gamma(\bar{B} \rightarrow \text{all})}$	$0.63 \pm 0.06 \pm 0.06$

from the same B and oppositely charged pairs from different B mesons, this is the result expected when b decays to c. The higher peak at 180° in the neutral-kaon distribution as compared to the charged-kaon distributions is due to the fact that we detect neutral kaons to higher momentum, for which the angular correlation effect for pairs from the same B is larger.

We use Monte Carlo simulations of the process $\Upsilon(4S) \rightarrow B\bar{B}$ and of the CLEO detector to produce the theoretical curves with which to fit the lepton-kaon angular distributions. The Monte Carlo simulation assumes a 100% branching ratio for $(b \rightarrow c)/(b \rightarrow \text{all})$ and 0.75 for the ratio $D^*/(D^*+D)$, and has been adjusted to match known features of B decay such as the multiplicity and the lepton and kaon momentum spectra.

We extract branching ratios through three two-parameter fits to the data. For lepton-kaon pairs involving higher-momentum kaons, θ_{lK} will more likely be near 180°. For this reason, we divide the charged-kaon data into kaon-momentum intervals of 0.2 to 0.4 GeV/c and 0.4 to 0.6 GeV/c when fitting the charged-kaon data. In all three fits, to like-charged-, oppositely-charged-, and neutral-kaon–lepton data, the eK and μK distributions are treated separately. Thus ten distributions are fitted. The results of the fits are shown as curves in Figs. 2(a)–2(c). One of the two theoretical curves in each figure is the distribution of included angle for lepton-kaon pairs coming from the same B (dotted curve) and has a strong peak at 180°. The other curve is the distribution for pairs coming from different B mesons (dashed curve) and is an isotropic distribution, except for detection-efficiency effects. The solid curve is their sum. The fitting parameters are the normalizations of the two theoretical curves. In each fit we measure a kaon branching ratio in semileptonic B decay by measuring the number of lepton-kaon pairs that come from the same B, and also a kaon branching ratio in all B decay by measuring the number of pairs that come from different B mesons. The values of χ^2/dof, 27/38, 36/38, and 21/18 for like-charged-, oppositely-charged-, and neutron-kaon–lepton fits, respectively, are in all cases acceptable.

Branching ratios are obtained by the multiplication of the branching ratio used in the Monte Carlo simulation in each case by the appropriate fitting parameter determined from the fit. The resultant branching ratios are given in Table I. The errors shown are statistical and systematic, respectively. Systematic errors come from various sources. The charged-kaon efficiency is known to $\pm 9\%$ (the statistical precision of the $\phi \rightarrow K^+K^-$ measurement). The neutral-kaon efficiency is known to within 10%. We varied the charged-kaon misidentification probability by $\pm 10\%$, recalculated the correction to the data, and refitted to arrive at a 2% systematic error due to this source. Likewise, we refitted the data after varying relevant Monte Carlo parameters within reasonable limits: the fraction of $\Upsilon(4S)$ decays that produce $B^0\bar{B}^0$, from 0.4 to 0.6, and the $D^*/(D^*+D)$ ratio, from 0.6 to 0.9. These variations contribute a 3% uncertainty to the measured branching ratios. The uncertainty in our estimate of the fraction of charged kaons with momenta between 0.2 and 0.6 GeV/c is the statistical error on the K_S^0 data we use to make the measurement, $\pm 5\%$. All systematic errors were combined in quadrature.

Our measurement for the sum of the $\bar{B} \to K^+X$ and $\bar{B} \to K^-X$ branching ratios $(0.85 \pm 0.07 \pm 0.09)$ compares well with the previous CLEO measurement[4] $(0.97 \pm 0.12 \pm 0.20)$, and our measurement for the $\bar{B} \to K^0/\bar{K}^0X$ branching ratio $(0.63 \pm 0.06 \pm 0.06)$ also agrees with the previous measurements by Brody *et al.* and Giannini *et al.*[4] of $0.72 \pm 0.12 \pm 0.14$ and $0.79 \pm 0.15 \pm 0.09$, respectively.

We have made a coarse measurement of the relative probability of $s\bar{s}$ creation from the vacuum in B decay to determine if it agrees with expectations. For the branching ratio $\bar{B} \to K^+X$, one expects contributions from Cabibbo-suppressed D decays (0.03, inferred from measurements by Baltrusaitis *et al.*[8]) from the decay chain $b \to cW^-$, $W^- \to \bar{c}s$, $\bar{c} \to \bar{s}X$ (0.07, based on phase-space considerations), and from $s\bar{s}$ pairs created from the vacuum (0.10, assuming 15% relative probability of $s\bar{s}$ pair creation). These sum to 0.20, in agreement with our measurement of $0.19 \pm 0.05 \pm 0.02$. If we take the other sources as given, the $s\bar{s}$ fraction of pairs created from the vacuum is determined to be $(14 \pm 8)\%$. Similarly, we can measure the $s\bar{s}$ creation rate using the difference between $\bar{B} \to K^0/\bar{K}^0X$ and $\bar{B} \to l^-K^0/\bar{K}^0X$. Using the measured value of 0.23 ± 0.12 and Monte Carlo simulations of the same quality, we obtain an $s\bar{s}$ creation fraction of $(7 \pm 11)\%$. The combination of the results from charged- and neutral-kaon data gives a relative probability of $s\bar{s}$ pair creation in B decay of $(11 \pm 7)\%$. This is in agreement with measurements from continuum fragmentation.[9]

The Monte Carlo prediction for 100% $b \to c$ and the data are in good agreement. In particular, the excess of K^- over K^+ in $\bar{B}$ semileptonic decay is 0.46 in the Monte Carlo simulation and 0.44 ± 0.09 in data, while the excess of K^- over K^+ in all $\bar{B}$ decays is 0.48 in the Monte Carlo program and 0.47 ± 0.07 in data. The decay chain $b \to c \to s$ causes this excess. Monte Carlo studies of $b \to u$, on the other hand, give equal branching ratios for K^+ and K^- to within 0.02. We can therefore use our inclusive kaon yields to set limits on $b \to u$. The two measures of excess K^- are derived from the same two fits. We find from studying the error matrices that the errors on the two excesses are highly correlated. The error on the measured excess is no smaller when both measurements are used. Therefore, we use only the more precise of the two measurements to extract $(b \to c)/(b \to \text{all})$. Dividing the measured excess $B(\bar{B} \to K^-X) - B(\bar{B} \to K^+X)$ of 0.47 ± 0.07 by that expected for 100% $b \to c$, we determine

$$(b \to c)/(b \to \text{all}) = 0.98 \pm 0.16 \pm 0.12,$$

where the errors are statistical and systematic, respectively. The systematic error is calculated under the same assumptions used to calculate the errors on our branching ratios. Plausible B-decay model variations produce a 5% systematic error in $(b \to c)/(b \to \text{all})$, uncertainties in the kaon efficiency give a 9% systematic error, and uncertainties in the charged-kaon misidentification rate cause a 1% systematic error. We add these in quadrature with a 5% error in the measurement of the fraction of the charged-kaon spectrum between 0.2 and 0.6 GeV/c to obtain a 12% total systematic error.

With this measurement we place a 90%-confidence-level lower limit on $(b \to c)/(b \to \text{all})$ of 0.68. This result is independent of the mass of the u-quark system, unlike the more restrictive limits[2] placed by analysis of the lepton spectrum from B decay. Recent studies of B decay to charm,[3] which use the measured D branching ratios,[8] suggest that B decay to noncharmed final states may be substantial. Although not definitive, the results reported in this Letter show no evidence of this.

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