Decay of B Mesons into Charged and Neutral Kaons

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Data on inclusive kaon production in e^+e^- annihilations at energies in the vicinity of the $\Upsilon(4S)$ resonance are presented. A clear excess of kaons is observed on the $\Upsilon(4S)$ compared to the continuum. Under the assumption that the $\Upsilon(4S)$ decays into $B\bar{B}$, a total of $3.38 \pm 0.34 \pm 0.68$ kaons per $\Upsilon(4S)$ decay is found. In the context of the standard B-decay model this leads to a value for $(b \to c)/(b \to \text{all})$ of $1.09 \pm 0.33 \pm 0.13$.

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The discovery of a broad resonance in e^+e^- collisions has been reported by two groups at the Cornell Electron Storage Ring.[1,2] The width of this new resonance, the $\Upsilon(4S)$, suggests that it decays into b-flavored mesons (B).[3] This assumption is strengthened by the observation of direct high-energy electrons and muons,[4] presumed to arise from the weak decay of the B meson.[5] In this paper we present data on the kaon content of $\Upsilon(4S)$ decays, which give additional information on the b quark decay.

The data sample contains 9200 hadronic events (3100 nb^{-1}) recorded with the CLEO magnetic detector[6] in the center-of-mass energy range below the $\Upsilon(4S)$ (10.378 to 10.528 GeV) and 21000 events (5600 nb^{-1}) on the $\Upsilon(4S)$. The latter corresponds to 5500 actual $\Upsilon(4S)$ decays. The central portion of the detector consists of cylindrical proportional and drift chambers inside an aluminum solenoid. Outside the coil is an octagonal array of planar drift chambers, hadron identifiers (four octants of Cherenkov counters and four octants of

dE/dx chambers), time-of-flight counters, and proportional-tube shower counters. Charged kaons were identified by time of flight and neutral kaons by the decay $K_S^0 \to \pi^+\pi^-$.

The time-of-flight system consists of 96 scintillation counters 2.3 m from the beam axis, covering 49% of the total solid angle. The observed time-of-flight difference for muons from the process $e^+e^- \to \mu^+\mu^-$ is zero with an rms spread of $0.36\sqrt{2}$ nsec.

Kaon identification by time of flight is limited to the momentum range $0.5 < p < 1.0$ GeV/c. The lower limit is imposed by absorption in the magnet coil, and the upper limit is set by the resolution of the counters. Figure 1(a) shows a typical mass plot for particles with momentum between 0.5 and 0.7 GeV/c. Clear pion and kaon peaks are visible.[7] Kaons are selected by requiring that the measured time of flight be within 1.2 nsec of that expected for a kaon, and greater than 1.2 nsec away from that expected for a pion or proton. A total of 1529 particles pass these kaon cuts, 384 on the continuum and 1145 on the $\Upsilon(4S)$.

We have measured the background in the charged kaon sample by looking at pions from K_S^0 decays and by using the independent particle identification from our dE/dx chambers.[8] The contamination is determined to be (26 ± 8)% for continuum events and (10 ± 3)% for $\Upsilon(4S)$ decays where the true K/π ratio is much higher.

A K_S^0 candidate is a positive-negative track pair reconstructed in the cylindrical drift chamber, with a vertex at least 7 mm away from the beam line and a net momentum vector extrapolating back to the primary event vertex. There is a momentum cut of 0.3 GeV/c on the kaon candidates, since below this momentum our K_S^0 acceptance (discussed later) is poor. The mass spectrum of such candidates, under the assumption that the secondary tracks are pions, is shown in Fig. 1(b). There is a signal of 1360 pairs within 20 MeV of the K^0 mass, 367 from the continuum and 993 from the $\Upsilon(4S)$, above a background of 562 as determined from the mass spectrum away from the peak.

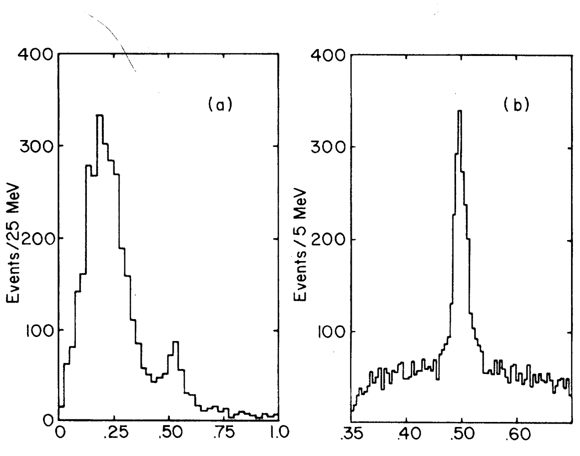

FIG. 1. (a) Mass distribution for particles with momentum between 0.5 and 0.7 GeV/c where $m^2 = p^2(1/\beta^2 - 1)$ and β is the measured velocity using time of flight. (b) Mass spectrum of all K_S^0 candidates.

Figure 2 shows the visible kaon cross sections in the vicinity of the $\Upsilon(4S)$. For this plot we have also included our data above the resonance. The enhancement due to the $\Upsilon(4S)$ is readily seen; the kaon cross sections rise by about 80% while the hadronic cross section is only 30% higher at the resonance.[1,2] The enhancement is also much larger than the 40% increase in charged multiplicity on the $\Upsilon(4S)$.[9] We see no such increase in kaon yields at the lower three Υ resonances.[10] This gives another indication that a new process is influencing the $\Upsilon(4S)$ decay.

We have used both Monte Carlo simulations and the data to determine our kaon detection efficiencies. The $K^\pm$ data, covering the momentum range 0.5 to 1.0 GeV/c, are corrected for the solid angle of the scintillation counters (0.49), track-matching efficiency (0.47), kaon decay (0.65 to 0.78), and the probability of passing the kaon time-of-flight cuts (0.32 to 0.99). The value of the track-matching efficiency is due to interactions in the coil ($\frac{1}{3}$ of an interaction length) and to other tracks causing confusion in the matching. This efficiency is found by measuring the percentage of tracks from the inner drift chamber which are matched to a hit time-of-flight counter after correction for solid angle and decays. We

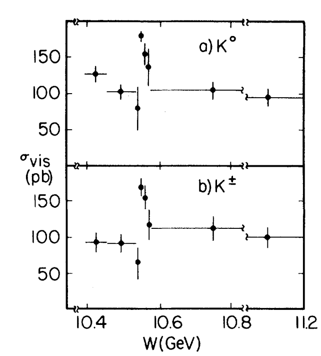

FIG. 2. Visible cross sections for (a) neutral and (b) charged kaons in the region of the $\Upsilon(4S)$.

see no difference in this efficiency between the continuum and the $\Upsilon(4S)$ data. The net $K^{\pm}$ acceptance is 11% for momenta between 0.5 and 0.8 GeV/c, falling to 4% at 1.0 GeV/c as the pion-kaon time-of-flight difference becomes smaller. After these corrections, we find, in the range $0.5 < p < 1.0$ GeV/c, 0.39 ± 0.07 charged kaons per event on the continuum and 0.79 ± 0.10 per $\Upsilon(4S)$ decay.[11]

The K^0 data, covering momenta above 0.3 GeV/c, are corrected for acceptance due to undetected K_L and $\pi^0\pi^0$ modes (0.34), pion detection efficiency (0.60), and the probability of a kaon decaying at a large enough radius (0.4) and being within the mass cut (0.85). The net K^0 efficiency rises from 5% at 0.3 GeV/c to 8% for momenta above 1.0 GeV/c. The increase in charged multiplicity at the $\Upsilon(4S)$ compared to the continuum leads to a 10% relative decrease in K^0 efficiency, due to increased track confusion. After these corrections, we obtain 0.65 ± 0.04 neutral kaons per continuum event and 1.13 ± 0.20 per $\Upsilon(4S)$ decay.[11] Figure 3 shows the corrected kaon momentum distributions for the continuum and $\Upsilon(4S)$ center-of-mass energies separately. The continuum background has been subtracted from the $\Upsilon(4S)$ distribution.

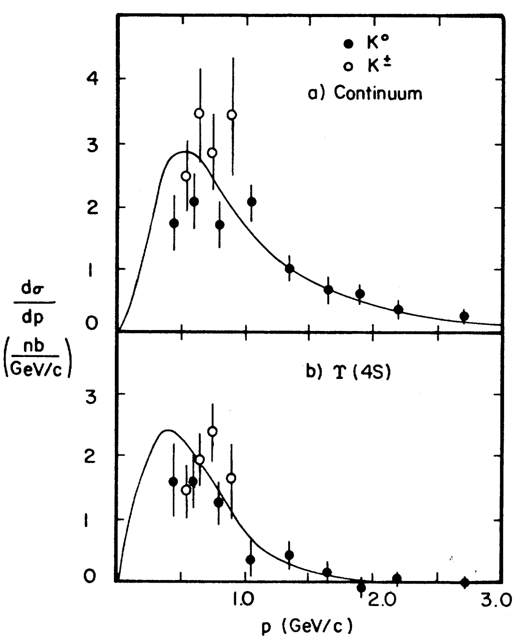

FIG. 3. Acceptance-corrected momentum distributions for (a) continuum events and (b) $\Upsilon(4S)$ events with the continuum subtracted. The curves are from Monte Carlo simulations of $e^+e^- \to$ (a) two jets, (b) $B\bar{B}$ where the b quark decays via the charmed quark.

We have also used Monte Carlo simulations to correct for kaons outside our momentum ranges and to test our sensitivity to various possibilities of b-quark decay. For the continuum, we simulate the process $e^+e^- \to q\bar{q} \to$ two jets, with quark pairs ($u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}$) created in proportion to the squares of their charges. The fragmentation into jets of hadrons[12] follows a standard parametrization of existing data[13] with the probability of creating $u\bar{u}$, $d\bar{d}$, and $s\bar{s}$ pairs from the vacuum in the ratio of 9:9:2.[14] Using the Monte Carlo momentum spectrum shown in Fig. 3(a) to correct for kaons outside our momentum ranges (0.65 for $K^{\pm}$ and 0.08 for K^0), we find the total number of charged and neutral kaons per continuum event to be 1.07 ± 0.19 and 0.73 ± 0.05, respectively (Table I). We assign an additional systematic error of 20% to these kaon yields to account for uncertainties in our detection efficiency and in the fraction of kaons within our detectable momentum ranges. These corrected kaon rates, as well as the scaled momentum distribution $(s/\beta)d\sigma/dx(x = 2E_k/E_{c.m.})$, are in agreement with the trend of previous measurements[15] at lower and higher center-of-mass energies.

For the resonance, we assume $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ with two variations of B-meson decay,[5] one in which the b quark decays via the c quark and another with the b decaying to the u quark. We use virtual W^- branching ratios to $l\bar{\nu}$, $d\bar{u}$, $s\bar{c}$, and $s\bar{u}$ of 21%, 60%, 16%, and 3%, respectively.[16] Quark pairs are created from the vacuum with the same flavor ratios used in the two-jet Monte Carlo computation.

Using the momentum spectrum shape from the $b \to c$ Monte Carlo computation shown in Fig. 3(b) to correct for kaons outside our momentum ranges (0.59 for $K^{\pm}$ and 0.21 for K^0), we find the average number of charged and neutral kaons per $\Upsilon(4S)$ decay over all momenta to be 1.94 ± 0.24 and 1.44 ± 0.24, respectively (Table I).[17] If the $b \to u$ Monte Carlo spectrum is used, the results change only slightly. The errors are statistical only; there is again an additional 20% systematic

TABLE I. The average number of charged and neutral kaons per event for the continuum and the $\Upsilon(4S)$. The errors are statistical only.

	Continuum	$\Upsilon(4S)$
$K^{\pm}$	1.07 ± 0.19	1.94 ± 0.24
K^0	0.73 ± 0.05	1.44 ± 0.24

error to account for uncertainties in the Monte Carlo calculation and in our detection efficiencies.

If we exclude $s\bar{s}$ pair creation from the vacuum, the standard B-decay model[18] predicts an average of 2.50 (0.90) kaons per $\Upsilon(4S)$ decay for $b \to c$ ($b \to u$). Using a 10% relative probability for $s\bar{s}$ creation in the Monte Carlo calculation raises the expected yield to 3.2 (1.6). Because of the systematic error, it is difficult to use our number of $3.38 \pm 0.34 \pm 0.68$ kaons per $\Upsilon(4S)$ decay to determine directly the relative amounts of $b \to c$ and $b \to u$. However, the ratio of kaons per $\Upsilon(4S)$ event to kaons per continuum event is much less sensitive to systematic errors. We measure 1.88 ± 0.28 for this ratio, where we expect 1.80 ± 0.10 for pure $b \to c$ and 0.95 ± 0.10 for pure $b \to u$. The last two errors are the remaining systematic uncertainties in the Monte Carlo calculation. Thus, although we cannot rule out some component of $b \to u$ in B decays, we find the fraction $(b \to c)/(b \to \text{all})$ to be $1.09 \pm 0.33 \pm 0.13$.

In conclusion, we have observed that the number of kaons per $\Upsilon(4S)$ decay is in clear excess of the number per continuum event. We attribute this to the weak decay of the b quark. The observed charged- and neutral-kaon rates favor the b-quark decay to the charmed quark.

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[16]These ratios give the correct B semileptonic branching fractions (see Ref. 4) and take into account mass

suppression factors for the c quark and the τ lepton.

[17]We have an independent measurement of the charged-kaon rates from our dE/dx chambers (see Ref. 8). The corrected number of charged kaons per continuum event using the dE/dx system is $0.91 \pm 0.09 \pm 0.11$ and the number per $\Upsilon(4S)$ decay is $1.80 \pm 0.32 \pm 0.22$.

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Coherence, Mixing, and Interference Phenomena in Radiative ψ Decays

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Ground-state and radially excited quarkonium configurations are all coherently produced in radiative ψ decays with amplitudes which depend on the wave function at the origin. Configuration mixing in the mass matrix due to annihilation into gluons also depends on the wave function at the origin and shows the same coherence. Small interference and mixing amplitudes can produce large coherent effects which invalidate conventional arguments used to distinguish between glueballs and quarkonia.

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Radiative decays of heavy quarkonium states into Okubo-Zweig-Iizuka–forbidden light-quark hadrons are of physical interest because they proceed via an intermediate state containing only gluons.[1,2] One might expect that bound states containing only gluons would be more easily produced in such a process than in transitions where quarks are present at all stages. However, considerable care is necessary in order to interpret data from radiative decays to distinguish glueball states from ordinary quarkonium states.[3-8] The states are at sufficiently high mass so that radially excited quarkonium configurations must be considered as well as ground-state configurations. Because both the ground and radially excited configurations are coherently produced from a gluonic state with an amplitude and phase which depends on the wave functions at the origin, large interference terms can arise in transition amplitudes. These effects can produce dramatic changes in transition probabilities from the predictions of simple nonet wave functions.[9] We discuss here two simple examples applicable to two recent gluonium candidates as illustrations of the difficulties of interpreting structure seen in this region.

As a first example, consider the radiative decay of a quarkonium vector meson into the η' and into the next pseudoscalar state with the quantum numbers of the η' which we denote by η_E. In the simple nonet quark models these would be the ground state and first radially excited states of the η' quark-antiquark configuration. However, radial mixing via annihilation into gluons will mix these two configurations[9-12]:

$$\eta' = \varphi_g \cos\theta - \varphi_r \sin\theta \tag{1a}$$

$$\eta_E = \varphi_g \sin\theta + \varphi_r \cos\theta, \tag{1b}$$

where η' and η_E denote the physical mesons and φ_g and φ_r denote the ground-state and first radially-excited-state wave functions. The phases of the wave functions are defined to make both φ_r and φ_g positive at the origin. The negative phase in Eq. (1a) is chosen because the interaction responsible for the mixing, namely annihilation and pair creation via a gluonic intermediate state, raises the mass of the η' above its unperturbed